SOIL COMPACTION VARIABILITY IN FLORIDA SANDY SOILS

By

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To my parents, José and Maria Lina,
to my wife, Beatriz,
to my sons, Luciano and Benjamin, and
to my daughters, Beatriz and Lina

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Abstract of Dissertation Presented to the Graduate School
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Major Department: Soil Science

Field studies were conducted to develop a better understanding of soil compaction variability in Florida sandy soils and to evaluate changes in soil compaction due to tillage and water management practices.

The tillage study included conventional tillage, conventional tillage plus in-row subsoiling, no-tillage, and no-tillage plus in-row subsoiling of Arredondo fine sand. Soil penetrometer resistance, bulk density, and water content were evaluated in relation to soil compaction at the end of eight yr. The relationship between soil penetrometer resistance and bulk density was not dependent upon water content, nor was there a distinct trend for the relationship between soil penetrometer resistance and water content due to the small range in the soil water content. Subsoiling to 33 cm reduced soil penetrometer resistance to less than 0.4 MPa in the top 20 cm, but it compressed the soil vertically at depths below 35 cm, and laterally at 35-cm depth as far as 30 cm.

Results from this study demonstrate that in-row subsoiling is a necessary practice to maintain soybean [*Glycine max* (L.) Merrill 'Bragg'] yields in a no-tillage system.

The water management study was conducted in the Institute of Food and Agricultural Sciences Irrigation Research and Education Park. After seeding soybeans, a uniform water rate was applied for 41 d, at the end of which four differential amounts of water were applied over a 35-d period. Water amounts in the 35-d period (including rainfall) were 160, 318, 384, and 411 mm for the following treatments: very low, low, medium, and high irrigation frequencies, respectively. For all treatments, soil penetrometer resistance increased with depth to a maximum between 2.6 and 3.1 MPa at the 45-cm depth, after which it decreased. Below 40 cm, soil penetrometer resistance increased slightly with an increase in the amount of water applied. Ninety percent of the soybean roots were in the 0- to 30-cm depth for the high frequency treatment and in the 0- to 75-cm depth for the very low frequency treatment. Soil compaction was increased 34% in the top 35 cm and root density decreased 26% in the top 15 cm when measured 78 d after two passes of tractor wheels in the row prior to planting. A soil penetrometer resistance of 2.5 MPa was found as critical for soybean root growth.

Soil penetrometer resistance varied widely when comparing different soil series used for citrus production. Values ranged from 0 to 74 MPa, being lowest for Kittaw, Kaliga, and Chobee series, and highest for the Oldsmar series. Results suggest that soil compaction may play a role in reducing the lifespan of citrus trees.

Donald L. Myhre
Chairman

CHAPTER I
INTRODUCTION

Growers may be confronted with several types of soil layers that result in poor root health by restricting water movement and root penetration. This is because soils are inherently variable as products of geological processes leading to soil deposit formation and of prevailing environmental conditions encountered during natural deposits.

Soil compacted layers restricting root growth can be formed by natural and/or man-made processes. According to Richardson (1929), a loose incoherent sand with a small content of silt and clay and free from electrolytes was favorable for the formation of an organic hardpan if the water table was within 25 to 63 cm of the surface during a part of the year. Later, Volk (1953) stated that a brown or brownish-black hardpan (spodic horizon) commonly found in palmetto flatwood soils has been formed as a result of alluvial movement and subsequent deposit of soil colloids and materials in solution under the influence of high soil acidity. Tillage pans, also known as plow pans or traffic pans, are distinct from the fragipan or spodic horizons which are morphological features of many soils of the southeastern United States (Soil Survey Staff, 1960).

In Florida, studies have been conducted to characterize compacted soil layers and their effect on crop and root growth (Campbell et al., 1974; Carlisle and Fiskell, 1967; Carlisle and Schoen, 1969, Fiskell, 1968; Fiskell et al., 1968, Kashirad et al., 1966, Kashirad et al., 1967; Pettry et al., 1965, Richardson, 1929, Volk, 1953).

It may be helpful to consider soil compaction as a two-step process. First, the force applied must be sufficient to break the fabric strength of the soil and fragment structural peds and, second, the resulting fragments must be pushed into a compact arrangement. When a pan forms in a sandy soil it tends to remain, and the added pressure it receives each year adds to the compaction of the pan.

The overall objective of the dissertation research was to develop a better understanding of soil compaction variability in Florida sandy soils and to evaluate changes in soil compaction due to tillage and water management practices.

This dissertation is divided into seven parts. Chapter II is a review of the literature for the total study. In Chapter III, the relationships among the factors of soil penetrometer resistance, bulk density, and water content are evaluated in a long-term soybean tillage system. In Chapter IV, soil compaction is related to tillage treatments and soybean biomass production. In Chapter V, water management treatments are related to soil compaction and soybean rooting patterns. In Chapter VI, soil compaction induced by traffic is observed for soybean rooting patterns. In Chapter VII, results of characterizing 10 mineral soils and one organic soil used for citrus production in Florida's 'flatwoods' are presented. Finally, in Chapter VIII the study is summarized and recommendations are provided for further work.

CHAPTER II
REVIEW OF THE LITERATURE

Compaction Process

Compaction involves a rearrangement and bringing together of solid particles. The energy required to compact soil may arise from rainfall, growth of plant roots, machinery traffic, animal traffic, and weight of vegetation and soil itself. The main forces causing compaction of agricultural soils, however, come from machinery and tillage implements used to manage and harvest the crop (Cohron, 1974, Graecen and Sands, 1980).

Voorhees (1977) reported that the total amount of wheel traffic put in a field during one growing season can be extensive. A 6-row operation covering a width of 4.3 m and using 0.46 m wide rear tractor tires will make enough wheel tracks, just from the tractor, to cover every space in the field approximately twice. During this process pressures from 0.14 to 0.35 MPa are commonly applied to soil by agricultural tractor tires operating at nominal inflation pressures of 0.07 to 0.10 MPa (Cohron, 1974). Jakobsen and Greacen (1985) studied the effect of very heavy loads in two podzolized dune sands. They found that, on previously undisturbed soil, the depth of wheel ruts increased up to 19 mm linearly with the logarithm of the number of passes, up to 27 passes. They found that, on tracks which had been used previously, new ruts were formed to a depth of 5 cm.

Only under exceptional circumstances do agricultural soils have sufficient strength to resist the loads applied to their surface by tires. When the elastic limit is exceeded, permanent strains and

structural failure result. Three primary types of forces are exerted on the soil during the passage of a driver wheel. These are the downward acting forces due to dynamic load on the wheel, the shear stress resulting from the torque acting around the axle, and vibration effects transmitted from the engine through the carcass of the tire. While all three types of forces are present for the driver wheels of tractors and harvesters, the wheels of trailed equipment will generally exert only a dynamic load on the soil (Soane et al., 1981b).

Factors Affecting Compaction

The condition of the soil affects its sensitivity to compaction processes. Sandy soils (e.g., Lamm sand, Aeric Haplaquods) compact quite readily when the soil approaches saturation (Volk, 1953). Any compacted soil which possesses some internal friction is fully capable of retaining indefinitely the pre-stressing by previous compaction (Burmister, 1965). Soils which are initially loose will show much larger increase in compactness during the first pass (and in subsequent passes, whereas those soils which have appreciable strength initially have compaction resulting from the first pass that will differ little from that which follows subsequent passes (Soane et al., 1981b).

Compaction under conventional pneumatic tires is related to the physical properties of both the soil and tire. Factors such as load, contact pressure, wheel slippage, tire dimensions, carcass construction, inflation pressure, forward speed, and the number of passes are involved. The inflation tire pressure, as well as the size and carcass strength of the tire, control the distribution of forces over the area of contact with the soil, effects which are influenced, primarily, by the initial strength of the soil. The forces at the tire-soil interface

and the initial soil strength control the magnitude and distribution of stresses in the soil beneath the wheel. These stresses and the compactability of the soil determine the kind and amount of soil strain (Cohron, 1974, Sands et al., 1981b)

Beside the effect of the wheels, tillage also may influence soil densification. The tillage process usually results in a less dense state of the total mass after the implement has passed, however, locally compacted soil can and does occur as a result of improper operations (Cohron, 1974). Volk (1953) was the first in Florida to clearly differentiate natural organic hardpans from plowsole pans. Plowsole or tillage pans are the result of pressure or pounding on the previously undisturbed subsoil.

In a literature review, Taylor (1974) reported that soil strength was affected by changes in water content and soil bulk density. He also noted that other changes affected soil strength including types and amounts of saturating cations, the number of particle-to-particle contacts, the types of clay mineral, and the amount and type of organic materials. Cassel et al. (1978) recommended that future characterization of mechanical impedance include sufficient measurements to isolate not only tillage effects, but also position and depth effects.

Compaction Affecting Soil Characteristics

When soil is compacted, the pore size, soil aeration, water infiltration rate, and saturated hydraulic conductivity are reduced, but soil strength and soil matric potential are increased (Roe and Taylor, 1962; Greacen and Sands, 1980, Jakobsen and Greacen, 1985; Potapov, 1985; Taylor, 1974, Voorhees and Lindstrom, 1983). Jakobsen and Greacen (1985) found that wheel traffic changed the physical properties of the

soil to a depth of at least 0.7 m. After nine years of imposing compaction in a Nicollet clay loam (Aquic Hapludolls), Blake et al. (1976) found that saturated soil hydraulic conductivity in the 25- to 85-cm depth was 2.6 times greater for the non-packed treatment plots compared to the packed plots. The latter plots drained to a higher water content above 50-cm depth, but a lower water content below 50-cm depth. Sopozhnikov et al. (1985) found an increase in the capillary-sorption potential and in the number of water-stable aggregates in the macrostructure of the soil with increasing load pressure. They observed that an increase in water stability was associated with a decrease in the porosity of aggregates and resulted in a decrease of the agronomic value of the soil structure. They found that the number of large pores decreased sharply and became less rounded. Under a load of 300 kPa the pores showed a tendency to orient themselves perpendicularly to the direction of load application. Pores < 6 μm in diameter remained stable during compaction under load ≤ 300 kPa. Voorhees and Lindstrom (1983) found that wheel-induced soil compaction reduced total porosity 10% (from 50 to 40%) at the 7.5-cm depth in a Nicollet silty clay loam.

Changes in bulk volumetric properties may not be as important to plant growth as the associated increased strength and the reduction of conductivity, permeability, and diffusivity of water and air through the soil pore system (Soane et al., 1981b).

Responses of Plants to Compaction

Plant growth and yield are likely to show optimum response at a certain level of compactness. The optimum compactness is related to soil type, crop growth stage, and climatic conditions (Soane et al., 1982). Soil structure can be extremely important to root growth in

fine-textured soils, but soil strength usually is more important than soil structure in sandy soils (Taylor, 1974). For example, the bulk density at which an cotton (Gossypium hirsutum 'Stormmaster') roots penetrated Amarillo fine sandy loam (Aridic Paleustalfs) depended upon the soil moisture (Taylor and Gardner, 1963). They reported that roots penetrate most soils partly by growing through existing voids and partly by moving soil particles from the path, but plants whose roots have small diameter near the tips can penetrate rigid soil volumes whereas roots with larger tips cannot. If the soil has no continuous pores that are large in relation to the root tip, elongation rates will depend on the magnitude of the external constraint. Size and frequency of the voids may control utilization of water and nutrients by the roots (Taylor, 1974). According to Taylor and Gardner (1963), the soil strength concept may be valid only when voids provide few or no avenues for roots to penetrate a high strength soil mass. Besides the physical effect which soil compaction imposes on roots, compaction increased the volumetric water content at residual field capacity, thereby increasing the volume of water per unit volume of soil available to roots (Greacen and Sands, 1980).

Corn (Zea mays L.) roots from a compacted sandy loam soil in India (Pribet et al., 1971) had more sclerified cells in the cortical and vascular tissue and in the region of pith, which may be considered as traits developed in such roots to resist external forces and hence prevent the deformation of interior cells. They stated that the development of more phloem elements in the roots from loosened soil may be significant as it helps in the transport of organic nutrients from above-ground points to the roots. Working with alfalfa (Medicago

sativa), Blake et al. (1976) found that non-packed plots displayed a more diffusive fine root distribution among the main root branches (first and second order root members) at all depths than did those on packed plots. Taproot (first order root members) branching in the surface 30 cm was much more evident in samples from packed than from non-packed plots. Packed plots generally showed a higher proportion of root weights in the surface 40 cm and lower proportions below 40 cm than non-packed plots.

Information is needed on variation in growth pressure among roots on the same plant, as well as growth pressure variations with time for a particular root (Taylor, 1974). Root responses to compaction are complex due to the numerous ways in which compaction can modify the physical properties of the soil. Laboratory studies using simplified media can often produce clear evidence for these relationships but, in the field, the complexity of soils results in poorer or negligible correlations of root growth with soil strength. Moreover, reduced root activity in one part of the soil profile may be compensated for by increased root growth elsewhere (Soane et al., 1982).

CHAPTER III
SOIL PENETROMETER RESISTANCE, BULK DENSITY, AND WATER CONTENT COMPARISONS IN A SOYBEAN TILLAGE EXPERIMENT

Introduction

Agricultural equipment used for seedbed and field preparation may include moldboard plows, rototillers, planters, subsoilers, and a number of other tools. Use of these tools along with tractors and harvesting equipment, which has become increasingly larger over the years, can result in some soil compaction (Voorhees et al., 1978). Compaction or mechanical impedance has been related to root growth (Taylor et al., 1966) and crop yield (Campbell et al., 1974; Taylor and Bruce, 1968). The degree of soil compaction has been determined by soil penetrometer resistance (SPR) or bulk density (BD) measurements (Freitag, 1971).

Use of the penetrometer to measure soil compaction is empirical (Freitag, 1971) and dependent on a number of variables including cone angle and size (Freitag, 1968, Gill, 1968), and operation (Carter, 1967).

Factors significantly affecting SPR readings include BD, soil moisture content (θ) (Campbell et al., 1974, Rhoads and Wright, 1981), depth (Bill and Cruse, 1985, Voorhees et al., 1978), position, organic matter content, tillage treatment, and the interactions among these parameters (Cassel et al., 1978).

Penetrometer resistance has been correlated to a number of parameters such as θ and BD. Correlation of SPR to θ is dependent on BD (Mirreh and Ketcheson, 1973) and soil texture (Warnaars and Eavis,

1972). Several researchers (Camp and Lund, 1968; Ehlers et al., 1983) have found better correlations of SPR to θ at high BD values. Campbell et al. (1974) found that SPR was correlated to BD for specific soils and θ values. Jakobsen and Greaten (1985) found that the log of SPR was highly correlated to BD of coarse-textured soils. Others (Cartet and Tavernetti, 1968; Freitag, 1968; Taylor et al., 1966) found a curvilinear relationship of SPR to BD, but the relationship was dependent on θ and texture.

This study evaluated the relationships among SPR, BD, and θ on a sandy soil. Comparisons were made on several different tillage treatments at different positions and depths.

Materials and Methods

Experimental Site

An oat (Avena sativa L.)/soybean [Glycine max (L.) Merrill 'Bragg'] multiple-cropping-tillage experiment was initiated in 1976 near Gainesville, FL. The soil at the site was an Arredondo fine sand (Grossarenic Paleudults).

Treatments

The treatments included (i) conventional tillage (CT), (ii) conventional tillage plus in-row subsoiling (CTPS), (iii) no tillage (NT), and (iv) no tillage plus in-row subsoiling (NTPS). Conventional tillage consisted of two 4-yr phases. The first phase involved the use of a moldboard plow and disk. The second phase consisted of rototilling to a depth of 15 cm 1 d prior to planting. A planter with an in-row parabolic subsoiler unit was used for subsoiling treatments to a depth of 33 cm.

Treatments were repeated annually at the same position in each plot. Plots were 10 m long and consisted of 12 rows spaced 76 cm apart. The experimental design was a randomized complete block (RCB), with four replications.

Soil Penetrometer Resistance

Measurements were made with a hand-operated recording penetrometer (Carter, 1967). The penetrating point consisted of a 30° circular cone with a base area of 1.29 cm^2 and a diameter of 12.83 mm (Agricultural Engineers Yearbook of Standards, 1983). The instrument error in measuring SPR and depth was ±0.141 MPa and ± 1.5 cm, respectively (D.E. Little, personal communication, 1984). The cone was pushed into the soil at a rate of about 30 mm s^{-1}, and the force required was graphically plotted as a continuous function of soil depth.

One single irrigation (40 mm) was applied to all plots by an overhead sprinkler 24 hr prior to SPR measurements on 2 and 3 July 1984. Readings were taken to a depth of 60 cm at five horizontal positions per row in a transect perpendicular across four soybean rows (Fig. 3-1). Although all five positions were used in the statistical analysis, only three (row, traffic, and no-traffic) were used in our discussion. At each position, three SPR readings (subsamples) were taken forming an isosceles triangle with sides of about 5 cm. The average of these three SPR readings was used for statistical analysis. Using a calibrated, graduated plastic overlay, values (kg cm^{-2} converted to MPa) at 5-cm increments were digitized (x, y coordinates) from the graph recorded by the penetrometer.

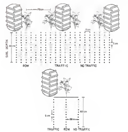

Figure 3-1. Dots in upper sketch show points selected for soil penetrometer resistance readings and dots in lower sketch show points for bulk density and water content measurements.

Soil Bulk Density and Water Content

Cores of soil samples were collected at points shown in Fig. 3-1 (lower sketch) with a double-cylinder hammer-driven core sampler (Blake, 1965). This device was driven vertically to the middle portion of each 5-cm layer of soil to obtain a total of 12 samples in the 0- to 60-cm soil profile. Samples were collected in the row position and 38 cm on each side of the row representing the wheel track (traffic) and the non-wheel (no-traffic) positions in two replicates of the four treatments. The samples were dried at 105°C and weighed for estimation of BD and θ.

Root-Pull Resistance

Measurements for root-pull resistance were taken on 4 Sept. 1984 by a method described by Gallaher (1984). Three side-by-side soybean plants were selected at five randomly selected sites in each plot. The three plants were tied together near the base with a string attached to a scale. A smooth and continuous force was applied to the scale until soybean plants were released from the soil. Root-pull resistance was represented by the maximum value recorded on the scale.

Soybean Yield

The four center soybean rows, each 3-m long in each plot, were harvested each year for seed production.

Statistical Analysis

The SPR data were analyzed as a split-split-split plot design (Table 3-1). The main plot was the effects of treatments, the first split was the effect of rows, the second split was the effect of positions, and the last split was the effect of soil depth. Subsampling variance was not of interest in this study and therefore was not estimated. The BD and θ data were analyzed as a split-split plot

Table 3-1. Summary of the results of the analysis of variance for three soil parameters.

Source of variation	Soil penetrometer resistance, MPa	Bulk density, Mg m^{-3}	Volumetric water content, m^{3} m^{-3}
	Level of significance†		
Main plots:			
Replicates	NS	NS	0.01
Treatments	NS	NS	NS
Rep. x Treat.	-	-	-
Sub plots:			
Rows	NS	-	-
Treat. x Rows	NS	-	-
Rep. x Rows (Treat.)	-	-	-
Sub-sub plots:			
Positions	0.01	0.01	0.01
Treat. x Pos.	0.01	0.05	0.05
Rows x Pos.	NS	-	-
Treat. x Rows x Pos.	NS	-	-
Rep. x Pos. (Treat. x Rows)	-	-	-
Sub-sub-sub plots.			
Depth	0.01	0.01	NS
Treat. x Depth	0.01	0.01	NS
Rows x Depth	0.01	-	-
Treat. x Rows x Depth	NS	-	-
Pos. x Depth	0.01	0.01	0.05
Treat. x Pos. x Depth	0.01	NS	NS
Rows x Pos. x Depth	NS	-	-
Treat. x Rows x Pos. x Depth	NS	-	-

† NS = non significant at $P < 0.05$, 0.05 = significant at $P < 0.05$, 0.01 = significant at $P < 0.01$; - = not applicable.

design. The main plot was the effects of treatments, the first split was the effect of positions, and the last split was the effect of soil depth. The root-pull resistance readings were analyzed as a RCB. The Waller-Duncan test in the SAS package (SAS Institute Inc., 1982a) was used for mean comparisons when only main effects were significant. The methodology of Cochran and Cox (1957) was used for mean comparisons when an interaction was present between two or more factors.

Results and Discussion

Selected physical properties for a typical Arredondo fine sand near the experimental site are given in Fig. 3-2 (adapted from Carlisle et al., 1981). The water contents were approximately .04 and .11 $m^3\ m^{-3}$ for soil water suctions of 1500 and 10 kPa, respectively. The water content near saturation (0.035 kPa) was between .36 and .40 $m^3\ m^{-3}$ for the entire profile. The Ap, E1, and E2 horizons were classified as fine sands. Bulk densities were 1.53 and 1.58 Mg m^{-3} for the Ap and E1 horizons, respectively. Saturated hydraulic conductivities were high, ranging from 23 to 27 cm h^{-1} in the upper 60 cm of the profile.

Soil Penetrometer Resistance

Results of analysis of variance (Table 3-1) indicated that position, depth, the two-way interactions of treatments by position, treatments by depth, row by depth, position by depth, and the three-way interaction of treatments by position by depth had a highly significant effect on SPR. The main effect of treatment was not significant at the 5% level. Mean values of SPR ranged from 0.13 to 3.48 MPa (Table 3-2) for the various treatments, positions, and depths.

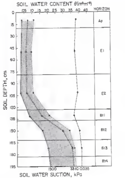

Figure 3-2. Soil water content at specified soil water suctions and horizon designations for Arredondo soil (adapted from Carlisle et al., 1981).

Table 3-2. Soil penetrometer resistance for the combination of soil profile depths, tillage treatments, and positions perpendicular to the soybean rows.

Soil depth cm	Treatment† NT Positions§ T	R	NT	NTPS Positions T	R	NT
	MPa					
5	0.93¶	0.73	0.76	1.01	0.20	0.83
10	1.63	1.40	1.64	1.52	0.33	1.55
15	1.96	1.86	1.96	1.81	0.35	1.85
20	2.35	2.26	2.31	2.09	0.40	2.04
25	2.97	3.02	2.92	2.30	1.59	2.27
30	3.18	3.37	3.20	2.47	2.71	2.55
35	3.01	3.15	3.00	2.61	3.08	2.76
40	2.66	2.74	2.63	2.51	2.99	2.77
45	2.39	2.34	2.26	2.21	2.64	2.50
50	2.09	1.99	1.94	1.86	2.19	2.13
55	1.86	1.75	1.76	1.60	1.82	1.75
60	1.68	1.64	1.56	1.46	1.61	1.58

Soil depth cm	Treatment CT Positions T	R	NT	CTPS Positions T	R	NT
	MPa					
5	0.69	0.28	0.13	0.94	0.16	0.18
10	1.30	0.52	0.39	1.64	0.33	0.40
15	1.95	1.36	1.54	2.15	0.31	1.13
20	2.51	2.15	2.34	2.56	0.40	1.86
25	3.02	2.79	3.07	2.93	1.29	2.39
30	3.27	3.22	3.48	2.96	2.66	2.82
35	3.05	3.26	3.29	2.92	3.23	2.99
40	2.72	2.86	2.80	2.73	3.13	2.97
45	2.38	2.50	2.37	2.42	2.89	2.63
50	2.08	2.07	2.03	2.10	2.50	2.34
55	1.89	1.78	1.76	1.82	2.16	1.99
60	1.65	1.62	1.55	1.55	1.88	1.78

† NTPS = no-tillage plus subsoiling, NT = no-tillage, CT = conventional tillage, CTPS = conventional tillage plus subsoiling.

§ T = traffic, R = row, NT = no-traffic.

¶ Least significant difference (LSD) for comparing any two means is 0.44.

Bulk Density

Bulk density was significantly affected by the main effects of position and depth along with the interactions of treatment by position, treatment by depth, and position by depth (Table 3-1). Maximum BD values (Table 3-3) were found at the 15- to 20-, 5- to 10-, 15- to 20-, and 25- to 30-cm depths for the WTPS, NT, CT, and CTPS treatments, respectively. Maximum BD was found in the NT plot and was located closer to the surface than the maximum BD of other treatments. Bulk density at the 5- to 10-cm depth was decreased ($P < 0.05$) by tillage (CT) or subsoiling (CTPS), but not for subsoiling under the NT treatment. Below the 10- to 15-cm depth, all treatments were statistically equivalent. A significant affect occurred from the interaction of position by depth (Table 3-1). Bulk density (Table 3-4) for all positions initially increased with depth, then decreased at a depth dependent on position. In the upper 30 cm of the profile, the traffic position had the highest BD, while the row position had the lowest. The no-traffic position had intermediate values.

Results of the analysis of variance (Table 3-1) indicate that the interaction of treatment by position was significant ($P < 0.05$). However, the mean separation procedure was not able to detect significant differences.

Water Content

For θ (Table 3-1) the main affects of positions, and the interactions of treatment by position and position by depth, were significant. The θ in the top 35 cm was highest in the traffic area, lowest in the row, and intermediate in the no-traffic area (Table 3-4). The change in water content may be due to the increase in that density at the no-traffic and row positions compared to the traffic position. Maximum θ for the traffic position was at the 0- to 20-cm depth, while

Table 3-3. Soil bulk density for the combination of soil profile depths and tillage treatments

Soil depth	Treatment†			
	NTPS	NT	CT	CTPS
cm	Mg m^{-3}			
0-5	1.48§	1.48	1.45	1.49
5-10	1.58	1.64	1.48	1.50
10-15	1.80	1.58	1.58	1.52
15-20	1.82	1.59	1.63	1.57
20-25	1.54	1.59	1.60	1.54
25-30	1.58	1.82	1.81	1.80
30-35	1.58	1.58	1.57	1.59
35-40	1.58	1.57	1.81	1.80
40-45	1.54	1.54	1.55	1.58
45-50	1.54	1.55	1.56	1.59
50-55	1.51	1.53	1.52	1.56
55-80	1.53	1.55	1.54	1.58

† NTPS = no-tillage plus subsoiling; NT = no-tillage, CT = conventional tillage; CTPS = conventional tillage plus subsoiling

§ LSD = 0.13 ($P < 0.05$) for comparing any two means

Table 3-4. Soil bulk density (BD) and volumetric water content (θ) for each position and soil depth combination.

Soil depth	Position		
	No-traffic	Row	Traffic
cm	BD, Mg m^{-3}		
0-5	1.47†	1.41	1.54
5-10	1.56	1.46	1.62
10-15	1.58	1.52	1.62
15-20	1.81	1.57	1.63
20-25	1.58	1.53	1.60
25-30	1.59	1.58	1.64
30-35	1.58	1.56	1.58
35-40	1.56	1.58	1.60
40-45	1.55	1.58	1.54
45-50	1.58	1.58	1.56
50-55	1.53	1.54	1.53
55-60	1.54	1.55	1.55
cm	θ, %		
0-5	8.71§	7.26	10.34
5-10	8.87	8.04	11.53
10-15	9.09	8.77	10.50
15-20	9.43	8.84	10.48
20-25	9.05	8.43	9.75
25-30	9.34	8.97	9.84
30-35	9.46	9.14	9.84
35-40	9.31	9.53	9.89
40-45	9.52	9.56	9.75
45-50	9.48	9.48	9.71
50-55	9.65	9.39	9.56
55-60	9.79	9.82	9.93

† LSD = 0.03 ($P < 0.05$) for comparing any two means.

§ LSD = 1.29 ($P < 0.05$) for comparing any two means.

the maximum θ for the no-traffic and row positions was found at depths greater than 35 cm.

<u>Relationship Between Soil Penetrometer Resistance and Bulk Density</u>

The overall correlation coefficient was $r = 0.51$ ($P < 0.01$) between SPR and BD (Table 3-5). Some researchers (Pidgeon and Soane, 1977; Schafer et al., 1968; Taylor and Gardner, 1963; Voorhees, 1983; Voorhees, et al. 1978) found that SPR was a more sensitive parameter than BD to estimate changes in the soil profile from compaction forces.

The correlation coefficient between SPR and BD was dependent on treatment, position, and depth (Tables 3-5 and 3-6). Correlation coefficients by treatments ranged from 0.26 ($P < 0.05$) to 0.70 ($P < 0.01$). Maximum correlation coefficient was for CTPS, followed by the CT, NTPS, and NT treatments. Correlation coefficients by position ranged from 0.27 to 0.62 ($P < 0.01$), being highest for the row position followed by the no-traffic and traffic positions. Correlation coefficients by depth (Table 3-6) were lowest at the 0- to 5-cm depth (0.32 NS) and greatest at the 5- to 10-cm depth (0.86) ($P < 0.01$). Generally, the highest correlations were found between the depths of 5 and 25 cm.

Correlation coefficients for treatment by position (Table 3-5) yielded a wide range of coefficients (0.04 NS to 0.81, $P < 0.01$). The two highest correlation coefficients (0.81 and 0.75, $P < 0.01$) were found at the row positions for the CTPS and CT treatments, respectively.

<u>Factors Affecting the Correlation of SPR and BD</u>

According to Ehlers et al. (1983), θ strongly affects penetrometer resistance measurements in loess soils. Campbell et al. (1974) found a good relationship of probe resistance to BD ($R^2 = 0.92$) based on θ. Differentiation of SPR readings into specific θ values should alleviate

Table 3-5. Simple correlation coefficients (r) between soil penetrometer resistance and soil bulk density for different treatments and positions.

Treatment	Position	r	n
Overall treatments and positions		0.51**†	288
-	No-traffic	0.52**	96
-	Row	0.62**	96
-	Traffic	0.27**	96
CT		0.60**	72
CTPS		0.70**	72
NT		0.26*	72
NTPS		0.43**	72
CT	No-traffic	0.60**	24
	Row	0.75**	24
	Traffic	0.41*	24
CTPS	No-traffic	0.73**	24
	Row	0.81**	24
	Traffic	0.33NS	24
NT	No-traffic	0.42*	24
	Row	0.28NS	24
	Traffic	0.04NS	24
NTPS	No-traffic	0.22NS	24
	Row	0.52**	24
	Traffic	0.21NS	24

† NS = non-significant at $P < 0.05$; * and ** = significant at $P < 0.05$ and $P < 0.01$, respectively.

Table 3-6 Simple correlation coefficients (r) between soil penetrometer resistance and bulk density (BD) or volumetric water content (θ) for different depths.

Soil depth	SPR versus BD	SPR versus θ
cm	r	
0-5	0.32 NS†	0.32 NS
5-10	0.66 **	0.38 NS
10-15	0.76 **	0.24 NS
15-20	0.75 **	0.24 NS
20-25	0.79 **	0.44 *
25-30	0.61 **	0.36 NS
30-35	0.45 *	-0.09 NS
35-40	0.46 *	-0.54 **
40-45	0.75 **	-0.54 **
45-50	0.61 **	-0.54 **
50-55	0.50 *	-0.32 NS
55-60	0.43 *	-0.31 NS

† NS = non-significant at $P < 0.05$; * and ** = significant at $P < 0.05$ and $P < 0.01$, respectively.

some of the error and increase the correlation of SPR to BD. Soil water content ranged from 0.06 to 0.13. Soil penetrometer resistance and BD were correlated for each one of seven 0.01 ranges in θ. Correlation coefficients for SPR versus BD for each range in θ values were highly variable, ranging from 0.21 NS to 0.71 ($P < 0.01$). The highly variable and relatively poor correlations of SPR to BD on the basis of specific θ values indicate that θ had a weak influence on SPR for this field experiment. This is a reflection of the small range in θ values.

Other factors that can influence the correlation between SPR and BD include soil texture, organic matter content, and field variability. Soil texture can alter soil strength and the soil moisture relationship. Warkaara and Eavis (1972) found that the relationship of SPR to matric potential was highly dependent on the sizes of the sand fractions present. Organic matter content may also influence the correlation between SPR and BD. Sands et al. (1979) noted that an increase in organic matter content decreased penetrometer resistance at constant bulk density. High correlations of SPR to BD are primarily limited to homogeneous soils under controlled conditions. Uniform observations and highly significant correlations under field conditions are difficult to attain (Bauder et al., 1981; Cassel and Nelson, 1979).

Relationship Between Soil Penetrometer Resistance and Water Content

Correlations between SPR and θ by treatments, positions, depths or their interactions (data not shown) were not significant and very low (maximum $r = 0.41$). Correlation coefficients of SPR to θ on the basis of depth (Table 3-6) were low and not significant for most of them. A negative relationship between SPR and θ has been observed by several researchers (Campbell et al., 1974; Ehlers et al., 1983, Gerard, 1965).

According to Shaw et al. (1942), under field conditions, no simple relationship exists between penetrometer readings and soil moisture even with an apparently uniform soil and trap. The poor correlation of SPR to θ should be expected for the soybean experiment because 40 mm of irrigation was applied to all plots 24 hr prior to SPR measurements.

Soil penetrometer resistance values could be predicted from a model consisting of depth, BD, the interactions of depth by BD, BD by gravimetric water content, and depth by gravimetric water content by BD, depth squared, and BD squared (Table 3-7 and Fig. 3-3). The determination coefficient for the above model was 0.81 ($P < 0.01$). The primary parameters associated with SPR were depth, depth squared, and BD. The rest of the terms in the model contributed only about 5% of the variation explained by the model. For prediction of SPR, gravimetric water content was used instead of volumetric water content because BD was used to estimate volumetric water content.

Relationship Between Crop Parameters and Soil Parameters

Bulk density can be further compared to root-pull resistance (Fig. 3-4). For root-pull resistance BD are the mean value at the row position in the 0- to 45-cm depth. For soybean yield BD are the mean values at the row position and at 30 cm in both sides of the row in the 0- to 50-cm depth. Root-pull resistance decreased with increasing BD. The decrease in root-pull resistance may be due to a decrease in rooting depth caused by increased compaction. Compared to NT, tillage (CT) and subsoiling (NTPS) increased the root-pull resistance by 0.3 and 1.0 kPa, respectively. The effect of subsoiling under conventional tillage did not significantly influence root-pull resistance. Root-pull resistance decreased 1.1 kPa for each 0.1 Mg m^{-3} of BD

Table 3-7. Results of multiple regression analysis for relationship of soil penetrometer resistance as a function of soil profile depth (D), bulk density (BD), gravimetric water content (GWC), quadratic terms, and interactions (Fig. 3-3).

Regression parameters†	Regression coefficients	Level of significance	R^2
Model	-	0.01	0.8182
Intercept	0.04046	0.87	-
Depth	0.09775	0.01	0.2979
Bulk density	-0.1620	0.06	0.2362
D^2	-0.001802	0.01	0.2449
BD^2	6.9814	0.01	0.0125
D x BD	0.1366	0.01	0.0117
GWC x BD	0.1979	0.02	0.000005
D x GWC x BD	-0.0092	0.01	0.0129

† Prediction of SPR at specific values of the regression parameters can be made by subtracting the following respective values: Depth = D minus 2.5; bulk density = BD minus 1.2012; gravimetric water content = GWC minus 1.27

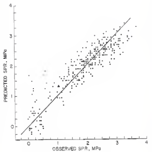

Figure 3-3. Observed soil penetrometer resistance (SPR) versus predicted soil penetrometer resistance when calculated as a function of depth, bulk density, and water content (Table 3-7).

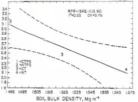

Figure 3-4. Relationship between root-pull resistance (RPR) with soil bulk density (BD) as a function of tillage and subsoiling treatments. Dashed lines are confidence limits at $P < 0.05$.

The 4-yr (1981-1984) average soybean yields were 2.0, 2.0, 1.7, and 1.6 Mg ha^{-1} for CTPS, NTPS, CT and NT, respectively (Fig. 3-5). Soybean yield decreased 3.8 Mg ha^{-1} for each 0.1 Mg m^{-3} increase in BD. Disturbance of the soil by tillage (CT) and subsoiling (NTPS) increased soybean yield 0.3 and 0.6 Mg ha^{-1}, respectively.

Table 3-8 shows mean values for all 4 treatments for the 1984 season. The BD was the average of values at the row position down to a depth of 30 cm. The same relationship between soybean yield and bulk density existed whether yield was expressed as a 4-yr average (Figs. 3-4) or for 1984 (Table 3-8).

Summary and Conclusions

Soil compaction resulting from heavy machinery is responsible for reduced crop yields through physical changes in soil. Soil penetrometer resistance (SPR), bulk density (BD), and volumetric water content (θ) were evaluated in relation to soil compaction in an 8-yr oat/soybean multiple-cropping tillage experiment initiated in 1976 near Gainesville, FL., on an Arredondo fine sand (Grossarenic Paleudults). Measurements for SPR, BD, and θ were made in 1984 for no-tillage (NT), conventional tillage (CT), no-tillage plus subsoiling (NTPS), and conventional tillage plus subsoiling (CTPS) in the row, no-traffic, and traffic positions at 5-cm depth intervals down to 60 cm. The overall correlation coefficient for SPR with BD was 0.51 (P < 0.01). Correlation coefficients of SPR with BD by treatments, positions, depths, and treatment-position interactions were highly variable, ranging from 0.04 to 0.86 (P < 0.01).

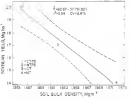

Figure 3-5. Relationship between soybean yield ($\hat{Y}$) with soil bulk density (BD) as a function of tillage and subsoiling treatments. Dashed lines are confidence limits at $P < 0.05$.

Table 3-8. Soybean yield, root-pull resistance, and bulk density for each tillage treatment in 1984.

Treatment†	Soybean yield	Root-pull resistance	Bulk density (Row, 0-30 cm)
	Mg ha^{-1}	kPa	Mg m^{-3}
CTPS	1.82 ± 0.52[§]	2.78 ± 0.13	1.47 ± 0.07
CT	1.34 ± 0.25	2.48 ± 0.15	1.50 ± 0.13
NT	1.20 ± 0.07	2.17 ± 0.24	1.58 ± 0.13
NTPS	1.78 ± 0.28	3.15 ± 0.15	1.47 ± 0.10

† CTPS = conventional tillage plus subsoiling; CT = conventional tillage; NT = no-tillage, NTPS = no-tillage plus subsoiling.

§ Means ± SD

Maximum correlation coefficients for each effect were 0.70 ($P < 0.01$) for the CTPS treatment, 0.62 ($P < 0.01$) for the row position, 0.86 ($P < 0.01$) for the 5- to-10 cm depth, and 0.81 ($P < 0.01$) for the CTPS by row interaction. The relationship between SPR and BD was not dependent upon θ, nor was there a distinct trend for the relationship between SPR and θ due to the small range in θ. The determination coefficient for SPR as a function of soil depth, bulk density, and gravimetric water content, was 0.81 ($P < 0.01$). Root-pull resistance and soybean yield were negatively related to BD. Determination coefficients for BD with root-pull resistance and soybean yield were 0.93 and 0.98, respectively.

CHAPTER IV

SOIL COMPACTION ASSOCIATED WITH TILLAGE TREATMENTS FOR SOYBEAN

Introduction

Passage of wheels of agricultural vehicles over soils is a common cause of soil compaction. Usually, the first pass of field equipment causes the greatest increase in soil compaction. Subsequent passes tend to compress soil at greater depths. If loads for vehicles do not exceed about 11 Mg per single axle, however, most of the compaction from wheel traffic will be restricted to the upper 20 to 30 cm of soil (Voorhees, 1984).

The penetrometer is a common instrument for assessing compaction, mechanical impedance, or soil strength (Gerard et al., 1982; Gill, 1968; Keene et al., 1981a). Soil penetrometer resistance readings also give an indication of the presence of compacted layers (pans) and relative resistance to root penetration (Volk, 1953). Soil penetrometer resistance values between 2.1 and 2.8 MPa have been observed to impede corn root growth (Taylor et al., 1966; Voorhees, 1984). In Florida, SPR values greater than 1.7 MPa were observed to impede penetration of maize roots in coarse-textured soils (Fiskell et al., 1968). Generally, SPR decreases as soil moisture content increases; therefore, soil compaction fluctuates with soil water during the growing season (Rhoads and Wright, 1981; Robertson, 1984).

Previous research in Florida (Rhoads, 1978) has shown that SPR under soybean rows was about 2.0 MPa less in subsoiled plots at the 15- to 20-cm depth than in plots without subsoiling. He found that

recompaction of the soil occurred, however, with a single pass of a tractor, and that root activity below on existing plow pan was greater in subsoiled than in control plots. Furthermore, he reported that subsoiling increased the two-yr average soybean yield by 743 kg ha^{-1}. In Georgia (Parker et al., 1975), subsoiling a sandy loam increased soybean yields 1.16 times (2.4 vs 2.8 Mg ha^{-1}) over an average of two-yr with four soybean cultivars. In Alabama (Thurlow et al., 1984), chiselling under the row increased yield of all cultivars tested at two planting dates in the first year but not in the next. In other Alabama studies (Touchton et al., 1984), the benefits of subsoiling depended on soil type.

A need exists to determine if long-range changes in compaction of sandy soils are associated with no-tillage practices, and whether such changes have any adverse effects on soybean growth and yield. In the early 1970s growers and scientists observed that soybean yields decreased after the second or third year of a continuous no-tillage system. Initially the objective of the present research was to test the hypothesis that the tillage system was associated with soybean response through some physical change in the soil. Subsoiling was evaluated as a factor. Specific objectives for the present study were (i) to compare the effect on soil compaction of conventional tillage to minimum tillage, with and without in-row subsoiling, as measured by SPR in areas of double-cropped soybean; (ii) to compare the effects of tillage and in-row subsoiling on soybean yield and on root-pull resistance (the force necessary to pull plants out of the soil); and (iii) to determine the relationship of SPR to soybean yield and to root-pull resistance values.

Materials and Methods

Experimental Site

The sections on experimental site, treatments, soil compaction, root-pull resistance, soybean yield, and part of the statistical analysis are presented in Chapter III. Additional information is given below.

Date of planting in 1984 was 28 May. Plant density was about 360 000 plants ha^{-1}. Pesticides were applied for weed control at planting and when plants were 30 to 40 cm tall and for insect control twice after pod formation. In the spring of 1984, soybean plants were in soil with residual fertilizer from the previous oat crop which had received a broadcast application of 20, 16, and 94 kg ha^{-1} of N, P, and K, respectively, after planting in Dec. 1983, and 67 kg of N ha^{-1} from ammonium nitrate in Feb. 1984.

Statistical analysis

All points indicated in Fig. 4-1 were used to evaluate SPR readings. Using an interpolation procedure (SAS Institute Inc., 1982a), values were estimated at 1-cm intervals for depth and 3-cm intervals for position. The resulting data were used to create the 3-dimensional plots, the contour plots, SPR ranges, and differences.

Results and Discussion

Soil Penetrometer Resistance

Results of the analysis of variance for SPR are given in Table 4-1. The model, which explained .87 of the total variation in the SPR data, included the effects of replicates, treatments, number of rows, positions, depths, and interactions. The main effects of position and

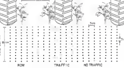

Figure 4-1. Schematic diagram showing sampling points for soil penetrometer resistance across four soybean rows from 0- to 60-cm in depth.

Table 4-1. Source of variation and level of significance for analysis of variance of soil penetrometer resistance in Arredondo fine sand following 8 yr of tillage and subsoiling treatments.

Source of variation	df	Level of significance†	R^2
Model	1 199	0.01	0.87
Main plots			
Replicates	3	NS	
Treatments	3	NS	
Rep x Treats. (a)	9	–	
Sub plots			
Rows	3	NS	
Treats. x Rows	9	NS	
Rep x Rows (Treats.) (b)	36	–	
Sub-sub plots			
Positions	4	0.01	
Treats. x Pos.	12	0.01	
Rows x Pos.	12	NS	
Treats. x Rows x Pos.	36	NS	
Rep x Pos. (Treats. Rows) (c)	192	–	
Sub-sub-sub plots			
Depth	11	0.01	
Treats. x Depth	33	0.01	
Row x Depth	33	0.01	
Treats. x Rows x Depth	99	NS	
Pos. x Depth	44	0.01	
Treats. x Pos. x Depth	132	0.01	
Rows x Pos. x Depth	132	NS	
Treats. x Rows x Pos. x Depth	396	NS	
Error (d)	2 640		
Total	3 839		

CV (a) = 149%
CV (b) = 58%
CV (c) = 35%
CV (d) = 21%
Mean = 2.05 MPa

† NS = non-significant at $P < 0.05$; 0.01 = significant at $P < 0.01$, – = not applicable.

depth were significant ($P < 0.01$). Also, the two-way interactions of treatment by position, treatment by depth, row by depth, and position by depth were significant ($P < 0.01$). The only significant three-way interaction was for the effect of treatment by position by depth. Treatments were compared taking into account the last interaction. Coefficients of variation were 149 and 21% for the main plot (treatment) and for the last split component in the design (depth), respectively.

Table 4-2 gives an overall view of percent distribution of SPR expressed in MPa ranges for treatments. Differentiation of SPR measurements in this manner allows for the comparison of the different treatments according to their effect on compaction. Soil penetrometer resistance values in the range 0 to 1.0 indicate low mechanical impedance, while values in the range 1.0 to 2.5 are intermediate, and values of 2.5 to 3.5 indicate compaction to an extent which may limit root penetration.

Conventional tillage versus no-tillage

No-tillage plots had the lowest volume of soil in the range 0 to 1.0 MPa. The effect of tillage was to decrease the volume of soil in the intermediate range of soil strength (SPR of 1.0 to 2.5 MPa), and to increase the volume of soil in the low and high ranges. These changes indicate that, although CT decreased SPR in some parts of the soil, tillage also increased SPR in other areas.

No-tillage versus no-tillage plus subsoiling

Subsoiling increased SPR values in the 0- to 1.0-MPa range and decreased SPR values in the 2.5- to 3.5-MPa range. This indicated that subsoiling in the NT plots decreased the overall effect of compaction by decreasing the volume of compacted soil.

Table 4-2. Percent of the top 80 cm of soil for each treatment having soil penetrometer readings (SPR) within three ranges of MPa.

Range in SPR	NTPS	NT	CT	CTPS
	Treatments†			
MPa	-----------	---%---	-----------	
0.0 to 1.0	20	11	21	25
1.0 to 2.5	52	54	41	37
2.5 to 3.5	28	35	38	38

† NTPS = no-tillage plus subsoiling; NT = no-tillage; CT = conventional tillage; CTPS = conventional tillage plus subsoiling.

Conventional tillage versus conventional tillage plus subsoiling

Subsoiling, compared to CT, increased the volume of soil with low SPR values, while decreasing the volume of soil in the intermediate SPR range of 1.5 to 2.5 MPa. Subsoiling had little effect in altering the volume of soil with high SPR. Why subsoiling under NT decreased SPR in the high range of SPR, but not under CT, is not well understood. The present data indicate that disturbance of the soil causes compaction deeper in the profile. Acceptance that CT causes some compaction, it may explain further compaction deeper in the profile due to passage of the subsoiler. Although subsoiling of the CT plots was beneficial in increasing the volume of soil with low SPR values, its effect was less than that of subsoiling the NT plots.

Conventional tillage minus no-tillage

Table 4-3 shows the distribution percentage for specific ranges of differences in SPR for specific comparisons of treatments. The comparison of CT minus NT indicates the effect of tillage on SPR readings. Positive values for this relationship indicate an increase in SPR from CT, while negative values indicate a decrease in SPR from tillage. The magnitude of this difference indicates the degree to which SPR has been altered. Since approximately 50% of the values of CT-NT were negative, it follows that CT increased compaction on the other half. The magnitude of the decrease was greater than the magnitude of the increase in SPR.

Conventional tillage plus subsoiling minus conventional tillage

Comparison of CTPS minus CT indicates the effect of subsoiling, under CT, on SPR measurements. Positive values for this relationship indicate that subsoiling increased SPR, while negative values indicate

Table 4-3. Distribution in percent of soil volume having negative or positive differences in soil penetrometer resistance (SPR) within defined ranges for specific treatment comparisons

Range of SPR differences	Treatments† compared		
	CT-NT	CTPS-CT	NTPS-NT
MPa		%	
-1.8 to -0.6	12	11	20
-0.6 to 0.0	38	36	43
subtotal	50	47	63
0.0 to 0.6	50	53	37

† CT-NT = SPR for CT (conventional tillage) minus SPR for NT (no-tillage); CTPS-CT = SPR for CTPS (conventional tillage plus subsoiling) minus SPR for CT (conventional tillage), NTPS-NT = SPR for NTPS (no-tillage plus subsoiling) minus SPR for NT (no-tillage)

a decrease in SPR from subsoiling. Subsoiling increased SPR 53% and decreased SPR 47% in the top 60 cm. The overall effect of subsoiling along with CT was to slightly increase SPR.

No-tillage plus subsoiling minus no-tillage

Similar to the above comparison, NTPS minus NT indicated the effect of subsoiling on NT plots. Positive values indicate increased SPR from subsoiling, while a negative value indicates a decrease in SPR. The most important point to note in Table 4-3 is that subsoiling on NT plots decreased SPR in 63% of the soil volume, while increasing it only for 37%. This indicated that the effect of subsoiling in decreasing SPR for the top 60 cm of soil was much greater for NT than for CT plots.

Three-Dimensional Computer Plots of SPR

Figure 4-2 gives a three-dimensional view of the effect of tillage and subsoiling as a function of soil depth on a transect across two rows of soybean. The thick arrows represent the traffic position, and the thin arrows the row position, with the no-traffic position in between the two rows of soybean (between the thin arrows). In all treatments SPR increased with depth to a maximum in the depth range of 30 to 40 cm and then decreased downward to the 60 cm. The most noticeable effect of treatments occurred on the subsoiled plots (CTPS and NTPS). The effect of tillage (CT) is less obvious than the effect of subsoiling. For soil with NT, the SPR values were very uniform across the two rows of soybean.

Two-Dimensional Computer Plots of Contour Isoresistance Lines

The top four 2-dimensional plots in Fig. 4-3 show contour isolines for SPR from plots in Fig. 4-2. In all treatments, SPR increased with depth. Maximum values (3.0 to 3.5 MPa) were found between depths of 30

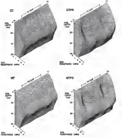

Figure 4-2 Computer plots showing an overall view of soil penetrometer resistance (SPR) in two directions, horizontally across a 2-row transect and vertically down the soil profile, for the 4 different treatments (CT = conventional tillage; NT = no-tillage, CTPS = conventional tillage plus subsoiling; NTPS = no-tillage plus subsoiling). The thin and thick arrows represent the two soybean rows and the two wheel tracks, respectively.

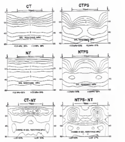

Figure 4-3. Contour plots of soil penetrometer resistance and differences in soil penetrometer resistance. Top four plots show isoresistance lines for CT (conventional tillage), NT (no-tillage), CTPS (conventional tillage plus subsoiling), and NTPS (no-tillage plus subsoiling). Bottom 2 graphs show isoresistance lines for MPa differences due to tillage (CT minus NT) and subsoiling (NTPS minus NT).

and 40 cm, depending on treatment and position. At the 60-cm depth, SPR values were between 1.5 and 2.0 MPa.

For soil with NT and at fixed depths, very uniform isoresistance lines were found across two soybean rows. Eleven percent of the area in the plot had an SPR equal to or less than 1 MPa, while 34% of the area had an SPR higher than 2.5 MPa.

For CT, isoresistance lines in the top part of the soil show the effect of tillage in reducing SPR at the no-traffic position compared to the traffic position. Twenty-one percent of the area with CT had an SPR equal to or less than 1 MPa, compared to 11% under NT. Tillage, however, had an opposite effect when the entire 60-cm profile is considered, since the area with SPR values greater than 2.5 MPa was 38%, or 1.12 times higher than under NT. Most of the increase in SPR was in the range between 3.0 and 3.5 MPa.

Isoresistance lines for NTPS show the localized effect of subsoiling at the row position. At fixed depths, SPR at the traffic and no-traffic positions apparently was not influenced by the in-row subsoiling. Twenty percent of the area for NTPS had an SPR equal to or less than 1 MPa, compared to 11 and 21% under NT and CT, respectively. Compared to NT values, NTPS had a better effect than CT in increasing the area in which SPR was less than 2.5 MPa. The above effect is greater considering that most of the decrease in SPR was in the range from 0 to 0.5 MPa, which was localized at the row position where the soybean plants grew.

Isoresistance lines for CTPS compared to CT show the effect of subsoiling at the row position. Twenty-six percent of the area had an SPR less than or equal to 1 MPa (1.24 times higher than CT). Compared to NTPS, CTPS had about 7 times more area in the range from 3 to 3.5 MPa.

Tillage and subsoiling influenced SPR with different intensities. The percentages of soil with SPR values between 2.5 and 3.0 MPa were 18, 18, 26, and 21 for NT, CT, NTPS, and CTPS, respectively. The corresponding percentages for SPR values between 3.0 and 3.5 MPa were 16, 20, 2, and 16, respectively. The largest contrast was for NTPS, which had the largest volume of compacted soil in the range from 2.5 to 3.0 MPa, but which also had the least volume of soil in the range from 3.0 to 3.5 MPa.

The lower isoresistance line of 2 MPa in NT was between 50- and 55-cm depth. The same isoresistance line for CT was around 55-cm depth, and closer to 60-cm depth when under CTPS. That seems that all of the isoresistance lines were further down the profile with disturbance of the soil (CT) and even more so when subsoiling (CTPS) occurred. The differences in SPR depended upon the lateral position for the CTPS. Even when tillage and subsoiling were imposed to a depth of 15 and 33 cm, respectively, their effects were noted at deeper depths. This observation implies that maximum movement of soil particles occurred in the immediate vicinity where soil was disturbed by compression effects of tillage and subsoiling implements. Lesser movement was transmitted to other soil particles as deep as 30 cm in the profile. Particle movement may have been deeper, but it is not possible to confirm that assumption since the sampling was only to the 60-cm depth.

The lower left plot in Fig. 4-3 shows differences for CT minus NT. A positive value for this relationship indicated an increase in SPR caused by CT, while a negative value indicated a decrease in SPR caused by tillage. The largest difference in SPR (> -1,2 MPa) was recorded at the no-traffic position near the 10-cm depth. The differences decreased more rapidly vertically than horizontally. At the 10-cm depth for the traffic position, tillage decreased SPR only by 0.3 MPa. At the no-

traffic position, the benefit of tillage is distinct in the top 22 cm of the soil. Deeper in the profile (20-50 cm) tillage increased SPR. Twenty-eight percent of the soil had decreased SPR from tillage in the range -0.3 to 0 MPa, compared to 44% for increased SPR from tillage in the range of 0 to 0.3 MPa.

Subtracting SPR values for NT from NTPS (lower right plot in Fig. 4-3) indicates the effect of subsoiling. Positive values for this relationship indicate that subsoiling increased SPR, while negative values represent a decrease in SPR due to subsoiling. Subsoiling caused a reduction in SPR at the row position for the 0- to 35-cm depth. No-traffic and traffic positions showed about the same difference in SPR in the top 0 to 35 cm of soil. Differences in SPR < -1.8 MPa were recorded at the row position at the 20-cm depth; however, subsoiling caused compaction of the soil directly below the row, where differences >0.3 MPa were recorded. Thirty-four percent of the soil had a difference in SPR between 0 and 0.3 MPa, compared to 25% for SPR values between 0 and -0.3 MPa.

Comparing CTPS minus CT (data not shown), 47% of the soil had a reduction in SPR due to subsoiling compared to 63% for the effect of subsoiling under NT. Sixteen percent of the soil had an SPR between 0.3 and 0.6 MPa, compared to 3% for the comparison of NTPS minus NT.

Other Graphical Comparisons of SPR

The SPR in the traffic position was similar for both CT and NT treatments (Fig. 4-4, lower left). At the no-traffic position (Fig. 4-4, lower right), CT resulted in a lower SPR at the 5- to 12-cm depth. Cross-hatched areas indicate where differences ($P < 0.05$) exist. Higher SPR for NT than CT within the surface soil (near 10 cm) agree with studies

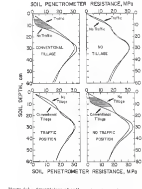

Figure 4-4. Comparisions of soil penetrometer resistance distributions with depth for traffic versus no-traffic interrows for CT and NT, and for NT versus CT for traffic and no-traffic interrows. Cross-hatched areas indicate where statistical difference ($P < 0.05$) occurred.

conducted in Mississippi (Hairston et al., 1984). Others (Gerik et al., 1984), however, found no difference in SPR when contrasting CT with NT for the 0- to 90-cm depth.

With CT, SPR was lower at the no-traffic than at the traffic position between the 5- and 10-cm depths, with a maximum difference of 0.9 MPa at the 10-cm depth (Fig. 4-4, upper left). At fixed depths, SPR for NT was the same at the traffic and at the no-traffic positions (Fig. 4-4, upper right).

Subsoiling affected SPR both vertically and horizontally in the top 60 cm of soil profile (Fig. 4-5, lower 3 plots). Subsoiling reduced SPR at the row and no-traffic positions. The effect of subsoiling was greater at the row position than at the traffic or no-traffic positions. There was, however, an increase in SPR in the row around the 50-cm depth due to the passage of the subsoiler. Close to the soil surface of the row position, the lack of difference in SPR resulted from a masking of the subsoiling effect from tillage. At the no-traffic position, a maximum difference was observed at the 20- to 30-cm depth.

For CTPS and NTPS, a reduction of SPR occurred at the row position compared with the traffic position (Fig. 4-5, upper plots). Comparing SPR between row and traffic positions, the row position under CTPS had lower values from the 5- to 25-cm depths and higher values at the 45-cm depth. The maximum differences were 2.2 and 0.5 MPa at the 20- and 45-cm depths, respectively. Under NTPS, the row position had lower SPR values at the 5- to 25-cm depths and higher values from the 35- to 40-cm depths, with maximum respective differences of 1.69 and 0.48 MPa at the 20- and 40-cm depths. Previous subsoiling experiments

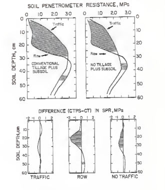

Figure 4-5. Comparisons of soil penetrometer resistance (SPR) distributions with depth for traffic versus row position for CTPS and NTPS treatments. The bottom 3 graphs show SPR differences for 3 positions (row, traffic interrow, and no-traffic interrow). Cross-hatched areas indicate where statistical differences ($P < 0.05$) occurred.

(Batchelor and Relelling, 1982) have indicated that coarse-textured soils were the most responsive to subsoiling.

Relation of SPR to Yield and Root-pull Resistance

Table 4-4 gives soybean yield, root-pull resistance, SPR, standard errors for the means of SPR, and the number of observations for each mean. Information in Table 4-4 was used to relate SPR to the soybean yield and root-pull resistance (Figs. 4-6 and 4-7).

Compared to NT, disturbance of the soil by tillage (CT) or subsoiling (NTPS) increased soybean yield 0.3 and 0.6 Mg ha^{-1}, respectively (Fig. 4-6). Soybean yield decreased about 0.9 Mg ha^{-1} for each MPa increment in SPR. Soil penetrometer resistance represented the average of readings at the row and 15 cm on both sides of the row, and at depths from 5 to 35 cm.

Compared to NT (Fig. 4-7), disturbance of soil by tillage (CT) or subsoiling (NTPS) increased the root-pull resistance values by 0.3 and 1.0 kPa, respectively. Apparently the disturbance of the soil caused a low SPR and consequently the taste had more opportunity to grow, proliferate, and become bound to the soil. Root-pull resistance values decreased 3.3 kPa per each unit MPa increment in SPR. Soil penetrometer resistance values represented the average at the row and 15 cm on both sides of the row, and from 5- to 60-cm in depth.

Comparison of Net Energy Requirements for Different Tillage Systems

The energy requirement for several field operations in crop production for a CT system is about 2 311 MJ ha^{-1}, compared to 1 599 MJ ha^{-1} for NT (Frye and Phillips, 1980). Some of the energy saved by NT is offset by the greater pesticide requirement for NT compared to CT. Phillips et al. (1980) reported that 109 more MJ ha^{-1} were necessary for

Table 4-4. Means used in regression analysis of soybean root-pull resistance versus soil penetrometer resistance (Fig. 4-6) and soybean yield versus soil penetrometer resistance (Fig. 4-7).

Treatment†	Soybean yield††	n	Soil penetrometer resistance¶	Standard error
	Mg ha^{-1}		MPa	
CT	1.7 b¶¶	16	1.915	0.069
CTPS	2.0 a	16	1.570	0.070
NT	1.4 c	16	2.241	0.054
NTPS	2.0 a	16	1.592	0.061

Treatment	Root-pull resistance	n	Soil penetrometer resistance§	Standard error
	kPa		MPa	
CT	2.476 b	12	2.042	0.044
CTPS	2.776 b	12	1.961	0.049
NT	2.165 b	12	2.172	0.035
NTPS	3.148 a	12	1.873	0.042

† CT = conventional tillage, CTPS = conventional tillage plus subsoiling, NT = no-tillage, NTPS = no-tillage plus subsoiling.

†† Each mean is based on 16 values (4 reps, 4 years).

¶ Each mean value is the average of soil penetrometer resistance readings in 1984 at the row position and 15 cm on both sides of the row, for the 5- to 35-cm soil depths.

¶¶ Mean values followed by the same letter are equal at $P < 0.05$.

§ Each mean is the average of soil penetrometer resistance readings in 1984 at the row position and 15 cm on both sides of the row, for the 5- to 60-cm soil depths.

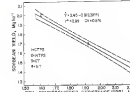

Figure 4-6. Relationship between soybean yield ($\hat{Y}$) and soil penetrometer resistance (SPR) based on 4 pairs of mean values. Means used in regression analysis and standard errors of means are given in Table 4-4. Broken lines represent confidence intervals ($P < 0.05$).

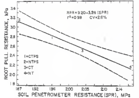

Figure 4-7 Relationship between root-pull resistance (RPR) and soil penetrometer resistance (SPR) based on 4 pairs of mean values. Means used in regression analysis and standard errors of means are given in Table 4-4. Broken lines represent confidence intervals ($P < 0.05$).

pesticide control in NT than CT. Frye (1984) gives a value of 820 MJ ha^{-1} for subsoiling, thus giving a saving of 17% energy in NTPS compared to CT.

Figure 4-6 shows that in-row subsoiling of NT plots resulted in a yield increase of about 0.6 Mg ha^{-1}. Assuming that the chemical energy content of soybeans is 23.6 MJ kg^{-1} (Murphy, 1981), the increase in yield amounts to 14 160 MJ ha^{-1} for an energy input cost of 820 MJ ha^{-1} (NTPS vs NT). It is clear that yield enhancement and energy conservation can be achieved by in-row subsoiling of this NT system. This is important to farmers producing soybeans without irrigation on sandy soils, because it saves production costs and increases profit.

Summary and Conclusions

Usually soybean yield decreases after the second or third year of a continuous no-tillage system in soybeans. In 1984, at the end of an 8 yr double-cropping oat/soybean 'Bragg' tillage experiment, soil compaction and its association to soybean yield and to root-pull resistance (the force needed to pull plants out from the soil) were studied. The soil series was an Arredondo fine sand (Grossarenic Paleudults). Treatments were no-tillage (NT), no-tillage plus in-row subsoiling (NTPS), conventional tillage (CT), and conventional tillage plus in-row subsoiling (CTPS). Forty d after planting soybeans, soil penetrometer resistance (SPR) readings were taken continuously to a depth of 60 cm at each sampling point in the row and at 15 and 30 cm on both traffic and no-traffic sides of the row. Row spacing was 76 cm. Under the no-traffic position, tillage (NT versus CT) decreased SPR from 1.64 to 0.39 MPa at the 10-cm soil depth. Maximum SPR (3.48 MPa)

occurred at the 30-cm depth for the traffic position with conventional tillage. Compared to no-traffic, traffic did not affect SPR in the NT In-row subsoiling at planting reduced SPR to less than 0.4 MPa in the top 20 cm, but compressed the soil vertically below 35 cm and at this depth the effect laterally was as far as 30 cm Tillage (CT versus NT) and subsoiling (NTPS versus NT) increased soybean yield 0.3 and 0.6 Mg ha^{-1}, respectively. Soybean yield was decreased about 0.9 Mg ha^{-1} MPa^{-1}. Tillage and subsoiling increased root-pull resistance values 0.3 and 1.0 kPa, respectively. Root-pull resistance decreased 3.3 kPa MPa^{-1} In-row subsoiling under the no-tillage system was the most successful treatment to alleviate soil compaction and to increase soybean yields.

CHAPTER V
EFFECTS OF WATER MANAGEMENT REGIMES ON SOIL PENETROMETER RESISTANCE AND SOYBEAN BIOMASS

Introduction

Soybean performance has been improved by irrigation (Boerma and Ashley, 1982; Pandey et al., 1984a, Reaseur et al., 1984; Reicosky and Deaton, 1979); however, precise irrigation timing (Doss et al., 1974; Griffin et al., 1985; Kadhem et al., 1985), proper cultivar choice (Kadhem et al., 1985), tillage (Martin et al., 1979), and rainfall (Scott and Batchelor, 1979) were crucial for high yields.

Besides the external factors, yield is determined also by the plant itself. The root strongly influences above-ground biomass production. By knowing how roots grow and what factors influence their development, it may be possible to optimize such factors and consequently improve root growth and increase yield.

Mayaki et al. (1976) found that, at physiological maturity (R10), 0.71 and 0.87 of the soybean root biomass (by weight) was in the upper 30-cm depth for irrigated and non-irrigated plots, respectively. Mitchell and Russell (1971) observed that 0.90 of the total amount of roots was in the upper 7.5 cm of soil. The main function of the root system is the absorption of water which carries most of the nutrients needed by the plant. Although the total mass of roots is important, a small portion of the root system may be responsible for a large portion of the water uptake (Pandey et al., 1984b, Stone et al., 1976). Also Reicosky et al. (1972) noted that 0.22 of the total soybean root mass

was in the capillary fringe area and absorbed 0.83 of the total water required by the plant.

Root growth and distribution are affected by several soil physical factors, one of which is soil compaction. It is difficult to measure the direct effect of physical impedance per se (Danielson, 1967). Soil penetrometer resistance is a measure of in-place strength of soils (Freitag, 1968), and has been associated with soybean and oat root growth (Ehlers et al., 1983; Rogers and Thurlow, 1973). Carlisle and Pinkell (1967) found that corn root penetration was partially or completely prevented by tillage pans, resulting in root deformities. Correlation of SPR and root growth under field conditions, however, is low (Ehlers et al., 1983). High variability of the data indicated that root growth was influenced by factors other than SPR.

Drs. Thomas R. Sinclair and Luther C. Hammond initiated a water management experiment in 1985 in the Institute of Food and Agricultural Sciences Irrigation and Education Park on the campus of the University of Florida, Gainesville. The objective of their study was to evaluate carbon fixation by the soybean plant and nitrogen fixation in the nodules in response to water deficits. The primary objective of the present study on the same site was to determine rooting patterns, aboveground soybean biomass production, and soil penetrometer resistance as affected by water management treatments.

Materials and Methods

Experimental Site and Cultural Practices

The experiment was located on a highly variable plot in unit two at the IFAS Research and Education Park. The predominant soil was Arredondo loamy sand (Grossarenic Paleudults). Other soils in the field were Lake

series (Typic Quartzipsamments) and Millhopper series (Grossarenic Paleudults). The site was subsoiled on 7 Mar. 1985 to a depth of 30 cm on 45-cm centers by a 5-cm tapered chisel, moldboard plowed to a depth of 20 cm on 11 Mar. 1985, and disked on 13 Mar. 1985.

Plots were fertilized on 13 Mar. 1985 with 53, 106, and 213 kg ha^{-1} of N, P, and K, respectively. Half of the fertilizer was applied preplant and the remainder as a sidedressing four weeks after planting. The initial application also included 0.4, 0.4, 1, 0.9, and 0.009 kg ha^{-1} of B, Cu, Fe, Zn, and Mo, respectively.

'Biloxi' soybean was planted on 20 Mar. 1985 with a hand planter in rows spaced 30-cm apart, and thinned to give a density of 2 M plants ha^{-1}. No attention was paid to the position of rows in relation to subsoiling.

Water Management Treatments

After seeding soybean, a uniform amount of water was applied for 41 d to all plots to obtain a vigorous and uniform stand that formed a canopy as rapidly as possible. After a closed canopy was formed, differential amounts of water were added over a 35-d period to the plots, beginning on 1 May 1985, to obtain a range of water stresses. The water management treatments included: very low irrigation frequency (VLF), low irrigation frequency (LF), medium irrigation frequency (MF), and high irrigation frequency (HF). Figure 5-1 shows dates of irrigation and amounts of water applied.

Soil water status was monitored by neutron scattering and gravimetric water content measurements. Data are presented for three selected dates. On 22 to 23 May, neutron readings for volumetric water contents were taken in two replicates at the following depths: 23, 30,

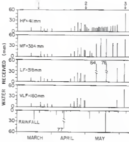

Figure 5-1. Rainfall distribution and irrigation applied during 1985. Total water for treatments (VLF = very irrigation; frequency; LF = low irrigation frequency, MF = medium irrigation frequency; HF = high irrigation frequency) included from 1 May to 5 June plus the rainfall for the same period. † 1 = subsoiling, 2 = starting of differential water regimes, 3 = ending of experiment.

45, 60, and 75 cm. On 28 May and 3 to 4 June, soil core samples at 15-cm increments, down to the 90-cm depth, were collected from all plots to determine the water content on an oven-dry weight basis.

Compaction Study

Prior to soybean planting, two passes of a tractor were made following the same wheel track to create two positions. The two positions are referred to as no-traffic (between wheel tracks) and traffic (in the tractor track). The tractor weighed about 2.5 Mg, and had a tire width of 45 cm. Soil water content at the time of traffic was near field capacity in the top 15 cm. The present Chapter deals only with the effect of water management treatments on soybean biomass production and SPR. The effects of traffic on soybean biomass and SPR are presented in Chapter VI.

Soil penetrometer resistance was measured using a recording penetrometer as described previously in Chapter III.

At 76 d after planting, a single irrigation (51 mm) was applied to all plots by an overhead sprinkler irrigation system. The purpose of this irrigation was to bring the water content to field capacity in all plots before taking SPR readings. According to Carter (1967) and Ehlers et al. (1983), it is desirable to have a uniform water content at specific depths, so that the SPR readings are not affected by differences in soil moisture. Twenty-four hr after irrigation, SPR readings were taken in each plot to a depth of 90 cm at 11 locations, 15 cm apart, in a perpendicular transect to tillage across five soybean rows. At each location (row or interrow), three SPR readings were taken (subsampling). The SPR subsampling locations formed an isosceles triangle with sides of 5 cm. The average of the three readings was used for statistical

analysis. The SPR curves were those recorded in the field and were subsequently digitized as described in Chapter III.

Soybean Biomass Production

Due to the original objectives of the experiment, the crop was not allowed to fully mature. At 76 d after planting, above-ground soybean biomass was harvested from two 1.0-m row sections taken at random in each water management plot, in both no-traffic and traffic positions. Total number of plants (NP) and above-ground soybean dry weight (SDW, g m^{-2}) (8 hr at 55°C) were recorded.

In order to estimate root production, soil core samples (7.5-cm diameter, and 15-cm long) were taken to the 90-cm depth. Samples were taken from each of two 1.0-m sections and composited by depth. Roots were separated from soil using a hydropneumatic elutriation system (Smucker et al., 1982). Root length density (RLD, mm root cm^{-3} soil), root weight density (RWD, µg root cm^{-3} soil), and root weight to root length ratio (RWD/RLD, µg root mm^{-1} root) were determined. Root length cm^{-2} of soil (LA, mm root cm^{-2} soil), and weight of roots cm^{-2} of soil (WA, µg root cm^{-2} soil), cumulated for the depths of 0 to 15, 0 to 30, 0 to 45, 0 to 60, 0 to 75, and 0 to 90 cm, were also determined (Marsh, 1971; Newman, 1966; Persad, 1982; Tennant, 1975).

Statistical Analysis

Soil water content data were analyzed as a split-plot design. Main plot was the effect of water management treatments and the first split was the effect of soil depth.

Soil penetrometer resistance data were analyzed as a split-split-split-plot design. Main plot was the water management treatment effect, first split was the effect of traffic, second split was the effect of location (row or interrow), and the last split was the effect of soil

depth. Subsampling variance was not of interest in this study and, therefore, not estimated.

Above-ground soybean biomass (SDW) and NF were analyzed as a randomized complete block (RCB) design. Root length density (RLD), RWD, and RWD/RLD ratio were analyzed as a split-split-plot design. Main plot was defined as the effect of water management treatments, first split was the effect of traffic, and the last split was the effect of soil depth. Cumulative LA and WA were analyzed as a RCB design.

The Waller-Duncan test in the SAS user's guide (SAS Institute, Inc., 1982b) was used for mean comparisons when only main effects were significant. The methodology of Cochran and Cox (1957) was used for comparisons when an interaction was present between two or more factors in the model. Values at 2-cm intervals for depth and 5-mm intervals for the amount of water applied were estimated for SPR, RLD, and RWD, using an interpolation procedure in a SAS graphics package (SAS Institute, Inc., 1982a). The resulting data were used to create three-dimensional graphs and contour plots.

Results and Discussion

The interactions between the water management treatments and traffic were not significant for the variables SPR, RLD, RWD, RWD/RLD, SDW, NF, LA, and WA. Therefore, the main effects for water management treatments are reported in the present chapter. The effects of traffic on the above specified variables are presented in Chapter VI.

Soil Water Content

The rainfall of 61 mm on 20 May brought all plots to the same soil volumetric water content for specific depths on 22 to 23 May (Tables A1 and 5-1).

Table 5-1. Soil volumetric water content (neutron method) for the combination soil depth and water management treatments (22-23 May 1985) after a rain of 61 mm on 20 May 1985.

Soil depth	Water management treatments†		Water content, θ
--- cm ---			----- % -----
23	VLF††		7.85 a#
	LF		9.01 a
	MF		8.49 a
	HF		8.83 a
		Mean	8.55 B¶
30	VLF		9.52 a
	LF		9.71 a
	MF		9.20 a
	HF		10.11 a
		Mean	9.64 AB
45	VLF		10.39 a
	LF		11.52 a
	MF		8.92 a
	HF		10.27 a
		Mean	10.27 A
60	VLF		10.37 a
	LF		11.82 a
	MF		9.34 a
	HF		11.03 a
		Mean	10.64 A
75	VLF		9.95 a
	LF		10.33 a
	MF		9.85 a
	HF		11.00 a
		Mean	10.29 A

† Differential amount of water received before soil water content determination was as follows VLF = 85 mm, LF = 229 mm, MF = 257 mm, and HF = 305 mm.

†† VLF = very low frequency irrigation; LF = low frequency irrigation, MF = medium frequency irrigation; HF = high frequency irrigation.

Water management treatment means within a soil depth followed by the same lower case letter are equal at the 0.05 level of probability.

¶ Soil depth means followed by the same upper-case letters are equal at the 0.05 level of probability.

The effect of the water management treatments on the soil water content was significant on 28 May (Tables A1 and 5-2). No rainfall occurred between 20 and 28 May, so that the soil water content on 28 May reflected the different irrigation frequencies.

The last differential water application was made on 29 May, so that by 3 to 4 June the soil gravimetric water content compared among treatments at specific depths, was statistically the same (Tables A1 and 5-2). The rapid soil water depletion during the 5 to 6 d may be the result of the high plant density.

Soil Penetrometer Resistance

Based on the results of water measurements described above at 20 May, it was assumed that the water content was the same for water management treatments at specific depths when SPR readings were taken.

The main effect of water management treatments on SPR was not significant; neither was the interaction of water management treatments with the effect of traffic and/or location (Table 5-3). Even when a highly significant interaction between water management treatments and soil depth existed, however, the mean statistical separation procedure used did not detect significant difference among means. That was due to the low F-value (1.71) and high coefficient of variation (CV = 215%). The three-dimensional display of SPR as a function of depth and water management treatments (Fig. 5-2), however, showed a clear and consistent tendency for a high SPR below the 30-cm depth with an increase in the amount of water applied. These SPR values increased with depth to a maximum at 45 to 50 cm, after which they decreased.

Isoresistance lines at 0.5 MPa intervals for data in Fig. 5-2 are shown in Fig. 5-3. Isoresistance lines in the top 30-cm depth were

Table 5-2. Soil gravimetric water content (%) for the combination of soil depth and water management treatments at two dates of sampling.

Soil depth	Water management treatments	Dates of sampling: 28 May†	Dates of sampling: 3-4 June††
--- mm ---		------- % -------	
0-15	VLF‡	2.15 c¶	1.53 a
	LF	1.60 c	1.70 a
	MF	3.50 b	1.88 a
	HF	5.95 a	1.48 a
	Mean	3.30 E§	1.59 D
15-30	VLF	2.75 c	2.18 a
	LF	1.90 c	2.48 a
	MF	3.98 b	2.00 a
	HF	6.65 a	2.08 a
	Mean	3.82 D	2.18 C
30-45	VLF	3.98 b	3.08 a
	LF	2.75 c	3.45 a
	MF	5.13 a	3.28 a
	HF	5.13 a	3.83 a
	Mean	4.24 C	3.41 B
45-60	VLF	4.50 ab	3.85 a
	LF	3.85 b	4.13 a
	MF	5.38 a	4.20 a
	HF	5.20 a	4.35 a
	Mean	4.73 AB	4.13 A
60-75	VLF	5.50 a	3.80 a
	LF	4.23 b	4.38 a
	MF	5.23 a	4.03 a
	HF	5.00 ab	4.20 a
	Mean	4.99 A	4.10 A
75-90	VLF	4.50 a	3.75 a
	LF	4.23 a	4.35 a
	MF	4.90 a	3.95 a
	HF	4.48 a	3.98 a
	Mean	4.53 BC	4.01 A

† Differential amount of water received before first sampling was: VLF = 89 mm, LF = 229 mm, MF = 295 mm, and HF = 340.
†† The day after sampling on 28 May, water was applied as follows: VLF = 20 mm, LF = 38 mm, MF = 38 mm, and HF = 20 mm.
‡ VLF = very low frequency irrigation; LF = low frequency irrigation; MF = medium frequency irrigation, HF = high frequency irrigation.
¶ Water content means for water management treatments within a column and within a depth followed by the same lower-case letter are equal at the 0.05 level of probability.
§ Water content means for soil depth within a column followed by the same upper-case letter are equal at the 0.05 level of probability.

Table 5-3. Summary of results of analysis of variance for soil penetrometer resistance (SPR), root length density (RLD), root weight density (RWD), and RWD/RLD ratio.

Source of variation	SPR	RLD	RWD	RWD/RLD
	--- Level of significance† ---			
Main plots				
Replicates	NS	NS	NS	NS
Irrigation	NS	NS	0.05	NS
Sub plots				
Traffic	0.05	0.01	0.01	NS
Irri. x Traff.	NS	NS	NS	NS
Sub-sub plots				
Depth	0.01	0.01	0.01	0.01
Irri. x Depth	0.01	0.01	0.01	NS
Traff. x Depth	0.01	0.01	0.05	NS
Irri. x Traff. x Depth	NS	NS	NS	NS
Sub-sub-sub plots				
Loc. x Depth	NS	-	-	-
Irri. x Loc. x Depth	NS	-	-	-
Traff. x Loc. x Depth	NS	-	-	-
Irri. x Traff. x Loc. x Depth	NS	-	-	-
CV (Irrigation) (%)	215	102	87	51
CV (Traffic) (%)	45	65	60	53
CV (Location) (%)	28	-	-	-
CV (Depth) (%)	26	55	67	50
Mean	1.8	6	112	13
R^2 (For model)	0.82	0.91	0.90	0.58

† NS = non-significant at $P < 0.05$; 0.05 = significant at $P < 0.05$; 0.01 = significant at $P < 0.01$, - = not applicable.

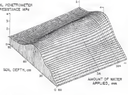

Figure 5-2. Three-dimensional plot of soil penetrometer resistance as a function of soil depth and amount of water applied. Thick lines represent observed values.

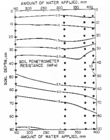

Figure 5-3. Isoresistance lines as a function of the amount of water applied and soil depth. Dots indicate means of observed values.

horizontal, indicating uniform SPR irrespective of water application. Consequently, roots in the top 30-cm depth may have had the same constraints in relation to soil compaction. Below 30-cm depth, SPR was numerically different among water management treatments. The slope of the isoresistance lines was negative at depths below 40 cm, indicating that, at fixed depths, SPR increased with the amount of water applied. In general, an SPR value >2.5 MPa has been found to significantly limit root growth (Rhoads, 1978; Rhoads, 1982; Taylor et al., 1966). In the present study the zone with SPR values >2.5 MPa existed between approximately the 30- and 60-cm depths. The fractions of data in the 0- to 90-cm depth with SPR values ≥2.5 MPa were 0.14, 0.15, 0.19, and 0.28 for VLF, LF, MF, and HF, respectively. Since the compacted layer (SPR ≥ 2.5 MPa) was at the 30- to 60-cm depths, it follows that roots may have grown easier through the thinner compacted zone under the VLF than under the HF treatment. From Figs. 5-2 and 5-3, it is obvious that the volume of soil with high SPR increased with the amount of water applied.

Soybean Biomass

Above-ground biomass

The main effect of water management treatments was highly significant for above-ground soybean biomass (SDW) (Table 5-4). The SDW increased with the amount of water applied from 180 g m^{-2} for VLF to 360 g m^{-2} for MF (Fig. 5-4). Soybean dry weight (SDW) increased to 0.73 g mm^{-1} of water applied. Kamagur et al. (1985) found that the total dry weight of 'Bragg' soybeans grown during 75 d on a sandy loam soil was approximately 175 and 275 g m^{-2} for the nonirrigated and irrigated treatments, respectively.

Table 3-4. Summary of results of analysis of variance for above-ground soybean biomass production (SOW), number of plants (NP), root length density cm^{-2} soil (LA), and root weight density cm^{-2} soil (WA) for several volumes of soil.

Source of variation	SOW	NP	Soil depth (cm) 0-15 LA	0-15 WA	0-30 LA	0-30 WA	0-45 LA	0-45 WA	0-60 LA	0-60 WA	0-75 LA	0-75 WA	0-90 LA	0-90 WA
	Level of significance†													
Main plots:														
Replicates	NS	NS	0.01	0.05	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Irrigation	0.01	NS	0.01	0.01	0.06	0.01	0.06	0.01	0.09	0.01	NS	0.05	NS	0.05
Sub plots:														
Traffic	0.05	NS	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Irri. x Traff.	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
CV (Irrigation) (%)	26	22	15	28	34	30	35	31	37	32	38	33	42	30
CV (Traffic) (%)	23	14	27	34	23	24	23	23	23	24	24	24	27	21
Mean	291	51	344	6 772	493	9 110	520	9 539	530	9 654	547	9 834	579	10 108
R^2 (For model)	0.82	0.72	0.84	0.79	0.87	0.87	0.88	0.88	0.88	0.88	0.87	0.88	0.86	0.87

† NS = non-significant at $P < 0.05$; 0.05 = significant at $P < 0.05$; 0.01 = significant at $P < 0.01$, - = not applicable.

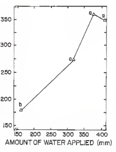

Figure 5-4. Above-ground soybean biomass production as a function of the amount of water applied. Values followed by the same letter are equal at the K-ratio of 100 under the Waller-Duncan test.

The same plant density was used in all plots during planting, however, some random variation in plant density among plots was observed at harvesting. In the present study, no overall relationship between SDW and NP was found. Water management treatments influenced the relationship between SDW and NP, however. The regression coefficients when expressing SDW as a function of NP were 6.58 ($P > 0.01$), 5.46 (NS), -0.68 (NS), and 0.29 (NS) for the VLF, LF, MF, and HF treatment, respectively. This finding indicates that as the amount of water applied increased, the relationship between SDW with NP diminished. Figure 5-5 shows the equation line for VLF treatment. Under moisture stress, soybean plots with low plant density did not produce enough biomass to compensate for low plant population. Soybean plots with low plant population and high water levels did, however, produce enough biomass to compensate for low plant density. Number of plants was not significantly affected by any of the sources of variation in the model (Table 5-4).

Below-ground biomass

Root length density (RLD). The interaction of water management treatments with soil depth was highly significant for RLD values (Table 5-3). Figure 5-6 shows a three-dimensional display of RLD as a function of the amount of water applied and soil depth. The RLD mean values changed faster with depth than with the amount of water applied. Least significant difference for comparing any two of these means is 4.4 mm root cm^{-3} soil.

For all water management treatments, RLD values decreased rapidly with depth. The decrease, however was greater as the amount of applied water was increased. Subtracting RLD values of the 45- to 60-cm depth from the 0- to 15-cm depth for the treatments VLF, LF, MF and HF yielded

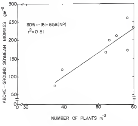

Figure 5-5. Regression of above-ground soybean biomass production (SDW) with the number of plants (NP) for the very low frequency irrigation treatment.

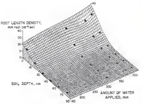

Figure 5-6. Three-dimensional plot of root length density as a function of soil depth and the amount of water applied. Data represent means of observed values.

differences of -15.5, -23.2, -22.2, and -28.3 mm root cm^{-3} soil, respectively. A slight and consistent increase in RLD at depths greater than 45 cm was also observed. For all treatments, there were three statistically different soil depths of RLD. The highest root concentration was in the first soil depth (0 to 15 cm), the zone with intermediate RLD values was in the depth 15 to 30 cm, and the third zone, which had the lowest RLD values, was in the 30- to 90-cm depth. Doty et al. (1975) reported that non-irrigated millet (*Panicum milliaceum* 'Pearl') and sweet corn ('Silver Queen') yielded more than did irrigated plots in a poorly-drained soil when rainfall exceeded pan evaporation. The reduction was attributed to an oxygen stress in irrigated plots.

The RLD in the top 30 cm of soil increased with the amount of water applied. At greater depths, RLD values were equal among water management treatments. There were about 15 mm root cm^{-3} soil at the 0- to 15-cm depth for VLF treatment compared to 28 mm root cm^{-3} soil for HF treatment. A RLD ratio of 1.81 (28/16) was obtained for the comparison of HF to VLF. Deeper in the profile (75 to 80 cm), however, the ratio of RLD values between the same treatments was only 0.24 (0.90/3.69). The change in ratios indicated that, compared to VLF, RLD was nearly doubled as a result of HF at the 0- to 15-cm depth, but was decreased by a factor of four deeper in the soil profile (75 to 80 cm). For the 20- to 80-cm depth, both VLF and HF treatments had the same root density, which was less than 4 mm root cm^{-3} soil.

Earlier, it was demonstrated that a compacted zone existed approximately at the 45-cm depth (Fig. 5-3), with a thickness dependent on irrigation frequency. More roots were found close to the soil surface (0 to 45 cm) and fewer roots in the 45- to 80-cm depth for HF

compared to VLF treatment. Whether this trend resulted from the high volume of water applied, or to the high SPR around 45-cm depth, or to a combination of these two factors, remains undetermined.

Root weight density (RWD). The statistical model for analyzing RWD explained 0.9 of the total variation in the data (Table 5-3). Coefficients of variation were lower (87 versus 102%) for the main plot and for the first split (60 versus 65%) when compared to their respective values when analyzing RLD. The above comparisons indicate that RWD may be a more precise method of estimating root growth than RLD. The least significant difference for comparing any two RWD means is 82 μg root cm^{-3} soil. The ratio between RWD values of 0- to 15-cm depth to those at 45- to 60-cm depth was 29, 40, 114, and 92 for the treatments VLF, LF, MF and HF, respectively. This indicates that the decrease of RWD values with depth was greater as increased amount of water applied (Fig. 5-7). Below the 45- to 75-cm depth, a slight but consistent increase in RWD was observed for all treatments. This increase was less with increase in the amount of water applied. The ratios of the RWD values at 75- to 90-cm depth to those at 45- to 60-cm depth were 3.6, 2.0, 2.7, and 0.9 for the treatments VLF, LF, MF and HF, respectively. The thicker compacted zone found in the HF treatment compared to the VLF treatment may have acted as a constraint for the roots to grow deep into the soil profile. Supporting the last statement are the results from Boliger et al. (1981), who found that root growth of soybean 'Bragg' under controlled conditions was affected not only by the resistance of a compacted sandy loam, measured as BD, but also by its thickness. They reported that the fraction of roots (by weight) below the synthetic pan was 0.36 and 0.10 for a thickness layer of 1 and 4 cm, respectively.

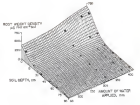

Figure 5-7. Three-dimensional plot of root weight density as a function of soil depth and the amount of water applied. Data represent means of observed values.

In the top 30 cm of the soil, RWD values increased with the amount of water applied from 279 μg root cm^{-3} soil for VLF treatment to 570 μg root cm^{-3} soil for HF treatment. A transition zone existed between the 30- and 60-cm depth. Below the transition zone, RWD values decreased with the amount of water applied. In the top 15 cm of soil, the HF treatment had twice the RWD of the VLF treatment. Deep in the soil profile (75 to 90 cm), however, VLF treatment had 6.4 times higher RWD than that for the HF treatment. Even though this last ratio was not statistically significant, the small difference may be very important in terms of root activity. Stone et al. (1976) found that, when 'Williams' soybean was grown in a silt loam soil, only a small portion of the root system could be responsible for much water uptake. They showed that irrigated plots had more root weight than nonirrigated plots in the 0- to 45-cm depth, but in the 45- to 75-cm depth the relation was reversed. This was very similar to the data in the present study.

Root weight density/root length density ratio (RWD/RLD). Table 5-3 shows the analysis of variance for the RWD/RLD ratio. Even when the CV values were lower than RLD or RWD, only 0.5% of the total variation could be explained by the model, and only the depth effect was significant. Values from the RWD/RLD ratio give an indication of root thickness (assuming equal dry matter per unit volume of root for all depths, replicates, and irrigation treatments). Roots were thicker close to the soil surface and decreased in diameter with depth. A mean value over treatments of 20.2 μg root mm^{-1} was recorded at the 0- to 15-cm depth, compared to 8.3 μg root mm^{-1} root at the 75- to 90-cm depth. It is not known if the decrease in root diameter with depth was a function of the plant itself or due to some other soil parameters. The VLF treatment had 16.8 μg root mm^{-1} root at the 0- to 15-cm depth compared to

21.3 μg root cm^{-1} root for HF. At the 75- to 90-cm depth, however, the value of RWD/RLD for VLF was 1.35 (10.1/7.5) times greater than the value for HF. Roots near the soil surface were thinner for VLF treatment and thicker deep in the profile when compared to that of HF. Since thicker roots were found deep in the soil profile for VLF compared to HF, and since the thickness of their respective soil volume with high SPR (>2.5 MPa) was lower for the former than for the last treatment, it is assumed that SPR significantly influenced root growth. Baligar et al. (1975) found that soybean root anatomy was altered by compaction, measured as BD. They found that, when compaction increased, there was also a gradual increase in the amount of thickening of the casparian stripe and the secondary walls of the xylem vessels that led to a large percentage of the root volume being occupied by cell wall material. All of the above strongly indicates that soil compaction is a very important factor influencing root growth.

Incremental root length density (LA). Table 5-4 shows the analysis of variance for LA, which represents the cumulated root data over several depths. The model explained between 0.84 and 0.88 of the total variation depending on depth of sampling. Coefficients of variation for the main plot increased from 15 to 42% for the 0- to 15- and 0- to 90-cm soil depths, respectively. The increase in CV rendered the effect of water management treatments to be not significant when considering the entire 90-cm soil profile. Figure 5-8 shows LA values as a function of the amount of water applied and the volume of soil sampled. Since LA is a cummulative value with depth and since most of the roots were in the upper 15 cm of soil, the LA for the rest of the depths sampled had approximately the same pattern as that shown for the first 15 cm. Least

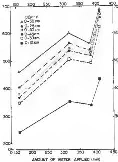

Figure 5-8. Cummulative length of roots (LA) over depths as a function of the amount of water applied.

significant differences under the Waller-Duncan test at the K-ratio of 100 for the 0- to 15-, 0- to 30-, 0- to 45-, and 0- to 60-cm depths were 59, 212, 234, and 249 (mm root cm^{-2} soil), respectively. The effect of water management treatments was only significant ($P < 0.05$) at 0 to 15 cm, however. The LA increased with the amount of water applied. For HF, 0.97 of the roots (663 mm root cm^{-2} soil) were found in the 0- to 60-cm depth, while only 0.82 of the roots (380 mm root cm^{-2} soil) were found at the same depth in VLF. With HF more than 0.90 of the total roots (625 mm root cm^{-2} soil) were found in the upper 30 cm of the soil while, for VLF less than 0.90 of the total roots (405 mm root cm^{-2} soil) were found in the 0- to 75-cm depth. Robertson et al. (1980) found that soybean root length per unit area in a fine sand to a depth of 150 cm was the same for both nonirrigated and irrigated treatments. If they had made LA comparisons at several depths, they might have found differences in the top soil as existed in the present study.

Incremental root weight density (WA). Table 5-4 shows the analysis of variance for WA cumulated over depth. The water management treatment effect was significant at all depths of sampling. Figure 5-9 shows WA as a function of the amount of water applied and the volume of soil sampled. Least significant differences for comparing water management treatments were 2 242, 3 217, 3 462, 3 650, 3 903, and 4 465 (µg root cm^{-2} soil) for the depths of 0 to 15, 0 to 30, 0 to 45, 0 to 60, 0 to 75, and 0 to 90 cm, respectively. The water management treatment effect was significant at all depths of sampling, compared to that at only one depth for LA, indicating that WA was more sensitive than LA to the amount of water applied. The WA values increased with the amount of water applied. After 384 mm of water, however, a slight decrease in WA was observed. For VLF, 0.92 of the roots (6 409 µg root cm^{-2} soil) were

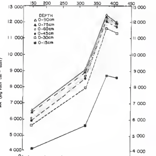

Figure 5-9. Cumulative weight of roots (WA) over depths as a function of the amount of water applied

in the top 0- to 75-cm depth, while 0.94 of the roots (11 252 μg root cm^{-2} soil) were found at the 0- to 30-cm depth for NF. Mayaki et al. (1976) worked with 'Williams' soybean on a silt loam soil and found that, at physiological maturity, 0.71 of the root dry matter was in the 0- to 30-cm depth and 0.91 in the 0- to 90-cm depth for the irrigated treatments, while the fractions for the nonirrigated treatment were 0.67 and 0.83, respectively. The findings in the present study for LA and WA indicate that the depth of sampling for root growth should vary according to the amount of applied water. Comparing results for LA and WA show that WA was less variable, and also more sensitive to the effect of water management treatments. Since obtaining WA data is less time-consuming and laborious, it follows that WA should be evaluated rather than LA.

Above-ground soybean biomass/root length density (SDW/LA) ratio. The above-/below-ground soybean biomass ratio (by weight) at specific depths was not influenced by either water management treatments or traffic, indicating the high relationship that existed between shoot and root growth. This means as the root increased in weight, the shoot also increased in weight in approximately the same proportion.

Association Among Soil and Crop Parameters

Correlation coefficients are given for several parameters (Table 5-5). Above-ground soybean biomass (SDW), LA, and WA were all highly positively correlated with the amount of water applied (I), indicating the benefit of irrigation on soybean biomass production. Other highly correlated variables were the above-ground soybean biomass (SDW) with the below-ground soybean biomass (LA, WA). It is assumed that as increase in root density increased the top portion of the soybean plant, and this effect should be transmitted to the yield. As expected SDW,

Table 5-5 Simple correlation coefficients among the parameters amount of water received (I), above-ground soybean biomass production (SDW), soil penetrometer resistance (SPR), root length density cm^{-2} soil (LA), and root weight density cm^{-2} soil (WA) (n = 32).

	SDW	0-15 cm depth		
		SPR	LA	WA
I	0.68**†	-0.25NS	0.49**	0.59**
SDW	-	-0.41*	0.40**	0.48**
SPR		-	-0.47**	-0.38*
LA			-	0.64*
Units	$g\ m^{-2}$	MPa	mm roots cm^{-2} soil	μg roots cm^{-2} soil
Mean	291	0.82	344	6.772
SD	105	0.24	126	3.094

† NS = non-significant at $P < 0.05$; 0.05 = significant at $P < 0.05$; 0.01 = significant at $P < 0.01$; - = not applicable.

LA, and WA values were negatively associated with SPR. These negative correlations showed that decreasing mechanical impedance was important for improving root growth and consequently increasing top growth and yield of soybean. Since correlation coefficients were significant only at the 0- to 15-cm depth, correlations for the other depths are not shown.

Table 3-6 shows mean values for RLD and SPR in selected soil layers for each water management regime. Two negative or inverse associations were found between RLD and SPR. One occurred in the 60- to 90-cm layer, where RLD decreased as SPR increased. The other negative association occurred when relating RLD values in the 60- to 90-cm soil layer with SPR values in the 30- to 60-cm compacted layer. The above findings indicate that RLD values below the compacted layer were a function of SPR values both in and below the compacted layers.

Summary and Conclusions

Irrigation is a practice that, when needed, improves crop performance. The effects of differential water management regimes on soybean 'Biloxi' biomass production and soil penetrometer resistance (SPR) were evaluated. The experiment was located on a well-drained Arredondo loamy sand (Grossarenic Paleudults) near Gainesville, FL. After seeding, a uniform water regime was applied for 41 d, at the end of which time four differential amounts of water were applied over a 35-d period. Water (including rainfall) received during the 35-d period was 160, 318, 384, and 411 mm for the very low irrigation frequency (VLF), low irrigation frequency (LF), medium irrigation frequency (MF), and high irrigation frequency (HF) treatments, respectively. At 76 d after planting, SPR values for all treatments increased with depth to a maximum between 2.63 and 3.08 MPa at the 45- to 50-cm depth, after which SPR values decreased. Below

Table 5-6. Root length density (RLD) in three zones of different soil penetrometer resistance (SPR) for each of four water management regimes.

Water management regime	Location in soil profile: 0-30 cm (Above compact layer)	30-60 cm (In compact layer)	60-90 cm (Below compact layer)
	RLD, mm root cm^{-3} soil		
Very low frequency irrigation	11.6	1.0	2.7
Low frequency irrigation	16.9	1.3	1.8
Medium frequency irrigation	16.4	1.1	1.3
High frequency irrigation	20.8	1.5	0.7
	SPR, MPa		
Very low frequency irrigation	1.34	2.32	1.25
Low frequency irrigation	1.26	2.53	1.44
Medium frequency irrigation	1.25	2.57	1.62
High frequency irrigation	1.30	2.77	1.72

the 40-cm depth, SPE increased slightly with an increased amount of water applied. In the 0- to 15-cm depth, root length density (RLD) increased from 16 to 20 mm root cm^{-3} soil, and root weight density (RWD) from 279 to 570 ug root cm^{-3} soil for the VLF and HF water regimes, respectively. More than 0.9 of the roots were located in the upper 30-cm depth for the highest water regime and in the upper 75-cm depth for the lowest water regime. Above-ground soybean biomass increased from 180 to 360 g m^{-2} for the VLF and HF treatments, respectively.

At present, there is no adequate explanation for the high SPE values found deep in the soil profile for the high frequency irrigation treatment applied when compared to the very low frequency irrigation treatment. Vepraskas and Miner (1986) suggested that moisture depletion by roots could account for high SPE. However, Table 5-2 shows that, deep in the soil profile, HF had more water content that did VLF, although statistically not significantly different. Besides, at the last sampled depths, HF had fewer roots than did VLF treatment. It would be interesting to see how particle-size distribution was related to the different water management treatments.

Root distribution, at specific depths, was dependent on the water management treatments. Soybean roots grew closer to the soil surface under the high frequency water treatment than under the rainfed condition. A reverse condition was found deep in the soil profile for the same treatments. High frequency irrigation during the first stages of soybean development would not be desirable if there is no certainty of enough water supply later in the season. Soybean roots tend to be concentrated in the top part of the soil under high frequency irrigation and may not be able to utilize deep profile soil moisture.

CHAPTER VI
EFFECTS OF WHEEL-INDUCED COMPACTION ON
SOIL PENETROMETER RESISTANCE AND SOYBEAN BIOMASS

Introduction

High yields and low economic inputs are necessary for increased farm profit. Increased yield can be achieved when optimum environmental conditions are provided for plants. Of great importance is the soil, which affects crop growth by its influence on root behavior. Compacted soils altered root anatomy of soybean and corn (Baligar et al., 1975; Fiskell et al., 1968), and reduced shoot dry mass and root length density of beans [Phaseolus vulgaris (L.)] (Asady et al., 1985). Wheel traffic caused compaction of the soil (Jakobsen and Greacen, 1985; Voorhees et al., 1978) and, when compaction higher than 2.9 MPa was achieved, no cotton 'Stormmaster' roots were found in a sandy soil (Taylor and Gardner, 1963). The plant population of spring barley (Hordeum vulgare) was reduced when cone resistance greater than 2.5 MPa was recorded (Ball and O'Sullivan, 1982). Compaction from traffic can affect other crop parameters such as the formation and development of soybean root nodulation (Voorhees et al., 1976). The objective of the present study was to evaluate the effect of wheel traffic (zero and two tractor passes) on SPR and soybean biomass production (above- and below-ground) grown on a sandy soil.

Materials and Methods

Experimental Site and Cultural Conditions

The site, soil type, tillage, fertilization, plot information, and date of planting were presented under the same heading in Chapter V.

Water Management

As above, the water management treatments were presented in Chapter V.

Compaction Study

As indicated in Chapter V, two passes of a tractor were made in the row following the same wheel track creating two conditions (or positions). The two positions will be referred to as no wheel traffic and two passes of wheel traffic. The SPR measurements were taken in both the traffic and no-traffic positions as described in Chapter V.

Soybean Biomass Production

Above-ground biomass in two 1.0-m sections of row was harvested at random in both traffic and no-traffic positions. Total number of plant (NP) and above-ground dry weight (SDW) were recorded for each position. The roots in the traffic and no-traffic positions were evaluated as described in Chapter V.

Statistical Analysis

The same procedure was used as described in Chapter V.

Results and Discussion

Soil Penetrometer Resistance

Soil penetrometer resistance increased with depth up to 2.78 MPa for no-traffic at the 45-cm depth and up to 2.82 MPa for traffic at the 40-cm depth. Soil penetrometer resistance decreased after these

depths. Cross-hatched areas indicate where statistical difference ($P < 0.05$) was present (Fig. 6-1). The least significant difference for comparing any two means is 0.24 MPa. Two passes of the tractor before planting were enough to increase SPR in the 5- to 35-cm depth measured 76 d later. Raij and O'Sullivan (1982) reported values of 1.1 and 2.2 MPa for normal and excessively wheeled plots, respectively, in a loamy soil at 30- to 120-cm depth. Similarly, Nelson et al. (1975) found that cone penetrometer indices were lowest for plots with no-traffic, compared to plots with 4 or 8 passes of a tractor. In the present experiment, for the average of the 5- to 45-cm depths, SPR was 1.2 times higher (1.94/1.59) in the traffic than the no-traffic position.

For both traffic and no-traffic conditions, approximately one-fourth of the 90-cm profile (Fig. 6-1) has SPR values ≥2.5 MPa, a value representing a limitation to root growth (Greacen and Sands, 1980, Taylor et al., 1966). According to Voorhees (1979), difference in SPR between wheel-tracked and non-tracked areas would be greater when the soil is drier.

Soybean Biomass

Above-ground biomass

Above-ground soybean biomass at 76 d after planting was 323 g m^{-2} at the no-traffic position and decreased to 260 g m^{-2} due to two passes of the tractor. Similar results were reported by Lindemann et al. (1982), who found that, 51 d after planting 'Corsoy' soybean on a clay loamy soil, above-ground soybean biomass was 239 and 157 g m^{-2} for 0 and 2 passes, respectively.

Below-ground biomass

Root length density (RLD). For both traffic and no-traffic positions, RLD decreased with depth (Fig. 6-2). The two tractor passes

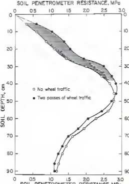

Figure 6-1. Soil penetrometer resistance as a function of soil depth and traffic. Cross-hatched area indicates where statistical differences occurred ($P < 0.05$). Data represent means of observed values.

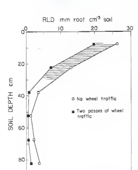

Figure 6-2. Root length density (RLD) as a function of soil depth and traffic. Cross-hatched area indicates where statistical differences occurred ($P < 0.05$). Squares represent means of observed values.

decreased RLD at all depths; however, change was significant only for the top 30 cm of soil. Root length density was highest at the 0- to 15-cm depth, at which depth the no-traffic position had a root density of 26 mm root cm^{-3} soil, while root density for the traffic position was only 0.74 of that value. The ratio of the RLD values of no-traffic to traffic position at the 0- to 15-cm depth was 1.34, while the same ratio for the 75- to 90-cm depth was 2.84 (3.21/1.13). Nelson et al. (1975) found by visual observations that soybean roots grown on plots without tractor passage were more developed and more extensive than roots on plots with tractor traffic.

Root weight density (RWD). For both traffic and no-traffic positions RWD values decreased with depth (Fig. 6-3). Traffic reduced RWD values at all depths, although it was significant only for the 0- to 30-cm depth. In the 0- to 15-cm depth the no-traffic position had a RWD value of 511 ug root cm^{-3} soil, while the RWD for the traffic represented only 0.77 of that value.

The decrease in root growth, either as RLD or RWD, at the middle of the sampled profile may be due to the high SPR found at the same depth. Raligar et al. (1981) found that soybean root growth was affected not only by the resistance of the compacted layer, measured as BD, but also by its depth and thickness.

Root weight density/root length density (RWD/RLD) ratio. Neither traffic, nor its interaction with depth, influenced the RWD/RLD ratio (Table 5-3).

Incremental root length density (LA). Due to the passage of the tractor wheel over the soil, cumulative LA was drastically reduced at all depths (Fig. 6-4). All means comparing traffic effect were

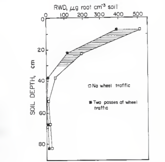

Figure 6-3. Root weight density (RWD) as a function of soil depth and traffic. Cross-hatched area indicates where statistical differences occurred ($P < 0.05$). Squares represent means of observed values.

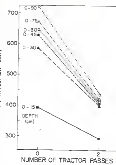

Figure 6-4. Cumulative LA over depths as a function of the number of tractor passes.

statistically different. The decrease (slope of lines in Fig. 6-4) in LA was greater as the depth sampled increased. That means LA values declined more rapidly as depth of profile increased. The passage of the tractor reduced LA by 25% (394 versus 294 mm root cm^{-2} soil) at the 0- to 15-cm depth, while at the 0- to 90-cm depth the reduction was on the order of 39% (721 versus 437 mm root cm^{-2} soil). Under traffic, 0.92 (401 mm root cm^{-2} soil) of the total roots were in the 0- to 30-cm depth, while approximately the same fraction of roots (673 mm root cm^{-2} soil) for the no-traffic position was achieved only when taking into account the 0- to 75-cm depth.

The change in LA and WA values with depth was defined as ΔLA and ΔWA. For the on-traffic position (Fig. 6-4), the ΔLA decreased when the depths 30 to 45 and 45 to 60 cm were considered. An increase in ΔLA was observed below the compacted zone. Data from Bar-Yosef and Lambert (1981) and Kashirad et al. (1967) support the statement that the reduction in LA at the middle of the sampled profile was due to the high SPR found at that depth.

Incremental root weight density (WA). The WA was depressed by traffic at all depths (Fig. 6-5). All means comparing traffic effect are statistically different. At the 0- to 15-cm depth no-traffic had 7 664 μg root cm^{-2} soil compared to 5 880 μg root cm^{-2} soil for traffic. For deep sampling (0- to 90-cm depth), the respective WA values were 12 253 and 7 964 μg root cm^{-2} soil. The decrease in WA due to traffic (slope of lines in Fig. 6-5) was more pronounced as the depth of the soil profile sample increased. For no-traffic 0.96 (11 819 μg root cm^{-2} soil) of the root weight was in the 0- to 75-cm depth, while for traffic 0.95 (7 630 μg root cm^{-2} soil) of the roots were in the 0- to 30-cm depth.

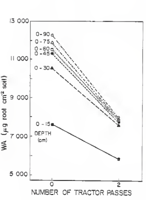

Figure 6-5. Cumulative WA over depths as a function of the number of tractor passes.

For no-traffic ALA and AWA decreased at the compacted zone and increased below. At the traffic position, the same behavior was observed for ALA, but not for AWA. It follows that deeper roots at the traffic position were thinner than those for the no-traffic position. The facts found for ALA and AWA indicated that root growth was reduced due to traffic and the high SPR, and roots were restricted to the upper soil (0 to 30 cm). Any root penetrating the compacted zone was able to grow but its growth depended on traffic effect. Voorhees et al. (1986) mentioned one advantage of compaction if it occurs deep in the soil. Compaction can reduce hydraulic conductivity and be beneficial under relatively dry conditions where decreased conductivity may conserve soil water, a concept fitting Florida conditions.

Relationship Between Selected Soil and Crop Parameters.

Figure 6-6 shows the relationship between RLD and RWD. The closer the equation lines the higher the correlation between RLD and RWD. Since RLD was more time consuming, more variable and less sensitive to the effect of water management and traffic than RWD, it follows that RWD should be preferred to estimate root growth.

According to Veprskas and Miner (1986), there is a need for field studies defining relationships between root growth and mechanical impedance. Relationships of root growth with SPR can be used to determine need for tillage or subsoiling, and may be also used in modeling for irrigation, since compaction effects the water holding capacity of soils and root distribution.

The relationship of RLD with SPR in Fig. 6-7 was found by separating the 90-cm soil profile into three 30-cm zones. All replicates, traffic conditions, and water management treatments are

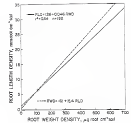

Figure 6-6. Relationship between root length density (RLD) and root weight density (RWD).

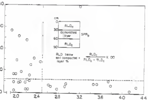

Figure 6-7. Percentage of root penetration as a function of soil penetrometer resistance at the 35-60 cm depth.

represented in Fig. 6-7. Only about 6% of the roots were found below the compacted layer when the SPR in the compacted layer (SPR_b) was in the range from 2.5 to 4.3 MPa. There was no apparent restriction for roots to pass through the compacted zone when SPR was <2.5 MPa. In relation to the low root density with low SPR, Webster (1979) stated that there is no reason to assume that roots will be present in all the soil volume that is suitable for root growth. The results from the present study support the findings from other researchers, that roots are strongly affected in their growth when soil is compacted to a SPR value greater than 2.5 MPa.

Figure 6-8 shows RLD and its relationship to SPR. The solid line (drawn by eye) represents the maximum RLD value that can be achieved at a specific value of SPR. In a soybean system similar to the one in the present experiment, no more than approximately 18 or 3 mm root cm^{-3} soil can be expected when the soil has an SPR of 2 or 4 MPa, respectively.

Table 6-1 shows mean values for RLD and SPR in selected soil layers for two traffic conditions. The effect of two passes of wheel traffic on reducing RLD was most evident in the two lower soil layers. The RLD in the 30- to 60- and 60- to 90-cm soil layer was 3.8 (1.99 + 2.52/0.48 + 0.74) times greater in the no-traffic than in the traffic position. The same comparison for the 0- to 30-cm soil layer gives a value of 1.5 (19.54/13.36). The effect of traffic on SPR was evident only in the 0- to 30-cm depth. The SPR in the 0- to 30-cm soil layer was 1.4 (1.51/1.07) times greater for the traffic than for the no-traffic position. Deep in the soil profile (30- to 60- and 60- to 90-cm depth), the same ratio yielded a value of only 0.98 (2.55 + 1.45/2.51 + 1.56). The results indicate that wheel traffic affects SPR mainly in the upper part of the soil profile, while RLD is affected greatly by soil compaction in the

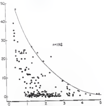

Figure 6-8. Root length density (RLD) relationship to soil penetrometer resistance (SPR).

Table 6-1. Root length density (RLD) in three zones of different soil penetrometer resistance (SPR) for each traffic condition

Wheel traffic	Root length density		
	0-30 cm (Above compact layer)	30-60 cm (In compact layer)	60-90 cm (Below compact layer)
	RLD, mm root cm^{-3} soil		
None	19.54	1.99	2.52
Two	13.36	0.48	0.74
	SPR, MPa		
None	1.07	2.51	1.56
Two	1.51	2.59	1.45

lower part of the profile, indicating that root growth at certain depth is a function of SPR.

Summary and Conclusions

Compacted layers, affecting crop growth, or tillage pans may be formed by mechanical operations or may be inherent in the soil. The objective of the experiment was to study the relationship of wheel traffic to soybean root distribution and soil penetrometer resistance (SPR) on an Arredondo loamy sand (Grossarenic Paleudults) near Gainesville, FL. After tillage and subsoiling but before planting, two passes of a tractor were made in the same wheel track (referred to as the traffic position). At 76 d after planting, soybean above-ground and below-ground biomass was harvested at the traffic (on the wheel tracks) and no-traffic (between wheel tracks) positions. At the same time, SPR readings were taken continuously to a depth of 90 cm across five soybean rows. From 5- to 45-cm depth, SPR increased from 0.32 to 2.78 MPa for the no-traffic position, and from 0.61 to 2.81 MPa for the traffic position. Traffic significantly increased SPR in the top 35 cm of soil by a factor of 1.34. For both the traffic and no-traffic positions, SPR decreased to approximately 1.1 MPa at the 90-cm depth. Traffic reduced above-ground soybean biomass from 323 to 260 g m^{-2}, root length density (0-15 cm) from 26 to 19 mm root cm^{-3} soil, and root weight density from 511 to 392 μg root cm^{-3} soil. Under traffic, 0.92 (401 mm root cm^{-3} soil) and 0.85 (7 630 μg root cm^{-3} soil) of the total roots by length and by weight, respectively, were restricted to the upper 30 cm of soil. Under no-traffic, 0.83 (673 mm root cm^{-3} soil) and 0.96 (11 819 μg root cm^{-3} soil) of the total roots by length and by weight, respectively, grew within the 0- to 75-cm depth. A SPR value of 2.5 MPa was found to be critical for root penetration.

CHAPTER VII
VARIABILITY IN SOIL COMPACTION OF 'FLATWOOD' SOILS USED FOR CITRUS PRODUCTION

Introduction

Citrus in Florida

During the last decade nearly three-fourths of all U.S. citrus was grown in Florida. Citrus in produced on about 290 thousand ha, which are distributed in 32 counties (Florida and Crop Livestock Reporting Service, 1985a, 1985b). Among the factors influencing citrus, blight is considered to be the most serious of the citrus declines and accounts for an annual loss of more than 0.5 million trees. Citrus blight was first reported in 1874 (Rhoads, 1936) but, as of now, no causal agent has been identified nor has any control been developed. However, growers can select rootstocks with a relatively low rate of blight incidence for replants or new plantings (Young et al., 1980; Young et al., 1984). Blighted trees exhibit altered Zn distribution (Smith, 1974) and plugged trunk xylem (Cohen, 1974). Soil physical characteristics appear to be important in hastening the development of citrus blight. Any abrupt change in the physical characteristics of the soil could influence citrus growth.

Diverse Nature of Soils

The diverse area planted to citrus in Florida implies a wide range of soils. Ten soil orders and about 300 soil series are present in Florida (A. Hyde, 1985, personal communication). Citrus is grown on many of these soils. Climatological variation, together with soil

chemical and physical characteristics, influence citrus production and longevity. Soil densification or compaction has been investigated by Florida researchers (Kashirad et al., 1966; Kashirad et al., 1967; Richardson, 1929, Volk, 1953).

Chesness et al. (1972) were concerned with peach (Prunus persica) decline in the Southern region of the U.S. They tried to characterize soil compaction and its relation to root development. At that time, life expectancy of peach trees was down from 20 to 8 yr. A similar condition exists in Florida, where a decline (blight) has jeopardized the citrus industry for about one century. A limited effort has been made in Florida (Myhre et al., 1986) to relate soil compaction to citrus tree condition.

Factors Leading to Compaction

According to Harris (1971), a change in the volume of soil when a load is applied can be attributed to the following conditions: i) a compression of the solid particles, ii) a compression of the liquid and gas within the pore spaces, iii) a change in the liquid and gas contents in pore spaces, and iv) a rearrangement of the soil particles. Since the solid and liquid phases are relatively incompressible and do not undergo appreciable volume change under loads usually applied to the soil mass, the change in state of compaction depends on movement of either the liquid or the solid phase, or both. The extent to which the soil particles can change positions by rolling or sliding is the major factor contributing to volume change for granular soils that are not saturated. For saturated conditions, the controlling factor for a large volume change is the rate at which liquid moves within the soil mass and, to a limited degree, from the soil.

Kashirad et al. (1966) and Kashirad et al. (1967) found that accumulation of Fe, Al, and Si were significantly greater in pan layers but this condition was not consistent for each soil series. They stated that soil organic matter probably helped to filter and encourage accumulation of some compounds in the pan which might be important in the cementation processes. Pumphrey et al. (1980) stated that sandy soils with 60 to 85% sand, 10 to 25% silt, and less than 5% clay were near ideal for maximum compaction. Florida soils have more sand and less silt and clay, but are not too much different from the above composition for maximum compaction. Campbell et al. (1974) identified soil layers with high soil strength in Paleudults of the Southeastern Coastal Plains. In the last indicated report, like in most of the published research, the soil compaction studies are usually limited to one soil type. However, a comprehensive study on a wide variety of soils was made by Larson et al. (1980) trying to relate compression curves to properties of agricultural soils and to present methods for predicting and describing the degree of compaction from an applied stress. They reported that in coarse-textured soils, particle size distribution rather than type of clay was the dominant factor in determining the degree of compaction from an applied stress.

Measuring Compaction

Knowing the presence of soil layers highly densified, the development of a uniform method for measuring soil hardness, and uniform scale of numbers for expressing it was recognized early (Stone and Williams, 1939). The soil cone index is the soil strength parameter upon which a methodology for continuously predicting trafficability of agricultural machinery could most likely be based (Wells and Treesuwan, 1978).

Penetrometer readings reflect the combined influence of bulk density, moisture content, depth, particle surface roughness, texture, and level of exchangeable cations, among other factors (Chesness et al., 1972; Cruse et al., 1981, Gerard, 1965; Wells and Treesuwan, 1978; Williams and Shaykewich, 1970). Within certain ranges, penetrometer resistance readings increased with bulk density, depth, and roughness of particle surfaces, and decreased with moisture content.

The final connecting link between soil strength as measured by cone penetrometer resistance and plant response is to establish values (or ranges) for the specific soil properties in relation to optimum root development (Chesness et al., 1972). In Florida (Carlisle and Fiskell, 1967; Fiskell et al., 1968; Kashirad et al., 1966; Kashirad et al., 1967), pan development was recognized by increased soil strength from pocket penetrometer resistance measurements and by limited root penetration of the pan or root distortion within the pan. They reported that root malformations were characterized by swollen, distorted root tips and flattened or distorted lateral root growth at or in the tillage pan. Tillage pans were found in several citrus groves and were thought to result from heavy equipment pressures. In the Florida sandy soils, soil strength, rather than increased bulk density, limited root growth. Roots of agronomic crops, and probably citrus, were likely to be restricted by pan formation. Compaction of the sand reduced the spaces so that bridging by cementing factors was facilitated.

Other studies in Coastal Plains soils (Campbell et al., 1974; Doty et al., 1975) have shown also that root growth was severely restricted due to compacted soil. Soil compaction is always an indirect cause of reduced plant activity; it can destroy a balance between the

requirements of the plant by limiting the supply capabilities of the roots (Taouse, 1971).

The objective of the present study was to describe the variability of soil compaction in soils of citrus groves in the 'flatwoods' of Florida, and to relate selected soil characteristics with tree condition.

Materials and Methods

Study Areas

Citrus groves were chosen to represent variations in 'flatwood' soils used for citrus production. Table 7-1 shows locations and selected characteristics of five groves. Prior to planting trees, the land was graded to form 1-, 2- or 4-row beds using soil from field ditches, perimeter ditches, and adjacent areas. The construction operation for ditches and beds often resulted in a very heterogeneous surface soil in some areas of the groves.

Grove A was selected because of its known high soil variability and subsequent non-random distribution of trees with citrus blight (Cohen, 1980). About 150 large 17 yr-old Valencia orange trees on rough lemon survived with relatively little blight decline in a 1-ha area of peat-like organic soil which contrasted greatly with surrounding mineral soil. About 75% of the trees on the mineral soil were removed because of blight disease, and then replanted in 1975. Grove C is included because of previous soil characterization and ground-penetrating radar studies (Shih, et al., 1986). This grove was planted in 1960. Ditches were 2.4-m wide at the top, 0.75-m wide at the bottom, and varied from 1.5 to 1.8 m in depth. Groves B, D, and E were

Table 7-1. Location of study sites and characteristics of citrus groves.

Grove designation	Owner	Location	Beds: No. of rows	Beds: Width m	Beds: Orientation	Distance between: Rows m	Distance between: Trees m	Rootstock/scion	Age yr
A	Coca Cola Co. (Minute Maid)	Indian River Co., FL 15 miles NW of Ft. Pierce; Bed 14, Block 721	4	30	N-S	8	7	Valencia/Rough lemon (Citrus sinensis (L.) Osbeck/C. Jambhiri Lush.)	30
							3.5	Valencia/Carrizo (C. sinensis (L.) Osbeck/C. sinensis x Poncirus trifoliata)	6-10
B	Okeechobee Land Co. (Shulock)	St. Lucie Co., FL 10 miles SW of Ft. Pierce; NE¼, NW¼, Section 4, T.35S. R.39E	2	16	N-S	8.4	5	Hamlin/Cleopatra mandarin (C. sinensis (L.) Osbeck/C. reticulata)	25
C	Coca Cola Co. (Hodson)	Martin Co., FL 22 miles E of Indiantown; SE¼, NW¼ Section 1b, T.39S. R.35E	4	30	N-S	6.4	5	Hamlin/Rough lemon	26
D	American Agronomics	DeSoto Co. FL 12 miles E of Arcadia; NE¼. SW¼. Section 29. T.37S. R.27E	2	16	N-S	7.3	3.7	Hamlin/Cleopatra mandarin	20
E	Mike Schlosler (Michigan)	DeSoto Co. FL 5 miles NW of Arcadia; NW¼, SW¼. Section 2. T.37S. R 24E	1	8.5	E-W	6.5	3.8	Hamlin/Sour orange (/ C. aurantium L.)	12

studied as a part of a phosphogypsum amendment experiment. The latter three groves contain soils which represent typical flatwood areas in south Florida, where increased citrus plantings have occurred due to recent freezes in central Florida.

Soil Sampling

In grove A, soil samples were collected on 8 Aug. 1985 at the tree dripline on the east side of trees (through the center of the bed) in the second row of a 4-row bed in a transect in the south-north direction. Sampling points were chosen to cover a wide range of soils and tree condition. Based on tree number and starting distance from the south end of the bed, the eleven locations were 5 (12 m), 12 (36 m), 27 (81 m), 36 (120 m), 41 (150 m), 52 (210 m), 54 (216 m), 84 (306 m), 85 (309 m), 96 (342 m), and 113 (393 m). Soils were described by Charles S. Gordon, SCS-USDA. Soil description included depth, thickness and boundary of horizons, color (moist), texture, structure, and consistence (moist). Samples were analyzed for pH (1:1, soil:water) and gravimetric water content expressed on an oven-dry basis.

In grove C, soil samples were collected on 10 Aug. 1983 at the tree dripline on the east side of trees (through the center of the bed) in the second row of a 4-row bed in a transect in the north-south direction. Two additional sites in the grove were chosen for digging a pit for sampling and describing the pedons, one [Floridana (Arenic Argiaquolls)] where citrus trees were healthy (between the second and third rows, about 255 m from the north end of bed) and another [Holopaw (Grossarenic Ochraqualfs)] where trees showed apparent citrus blight symptoms (between the second and third rows, about 75 m from the north end of bed). Soils were described by V.W. Carlisle, D.L. Myhre, and L. Carter

(SCS-USDA) (Shih et al., 1986). Soils were analyzed for pH. Groves B, D and E were not sampled.

Penetrometer Resistant Measurement

The SPR data were collected in the top 90-cm profile as described in Chapter V.

In grove A, SPR data were obtained on 8 Aug. 1985 at the same 11 locations where soil samples were collected (at the tree dripline on the east side of trees in the second row in a transect in the south-north direction). Additional SPR readings were taken on 5 June 1986 at two different positions in relation to each tree. Positions were: 1) at the dripper, about 100 cm north of tree trunk, and 2) at about 100 cm west of the dripper (through the center of the bed). Soil water content at the dripper position was estimated to be at or above field capacity; soil water potential 100 cm from the dripper was unknown but, from visual observations, assumed to be about -1 500 kPa.

In groves B, D, and E, SPR readings were taken in two sites at 20 plots. At each site three SPR were taken at the tree dripline. In grove C, SPR readings were obtained at two locations in relation to each sampling point.

Water Uptake by Trees

In grove A, trees located adjacent to the SPR sampling sites were tested for the volume of water uptake through the trunk of the tree (Cohen, 1974). A hole 1.5 cm in diameter and about 2.5 cm deep was made with a drill at about 10 cm above the bud union of the tree trunk. Using a 10 cm^3 syringe, water was injected into the tree trunk. Water uptake in 30 seconds was recorded.

Results and Discussion

Soil Classification and Description

Table 7-2 shows the parent material and the soil classification for each of 11 selected sites in grove A. Four soil orders and six soil series were identified in the 400-m transect (Fig. 7-1). Soil orders ranged from mineral soils with no distinct pedogenic horizons (Entisols) to developed soils (Alfisols), associated with soils high in organic material (Histosols and Mollisols). According to Carlisle et al. (1985), the parent material for Entisols is sandy marine sediments with poor drainage and high permeability. In these soils the water table is within depths of less than 25 cm for 1 to 3 months and recedes below 75 cm during normal winter and spring months. Alfisols have sandy and loamy marine sediments as parent material, with poor drainage and from rapid to moderate permeability, being rapid mainly in the surface or upper subsoil. Parent material for Histosols can be halophytic and non-woody hydrophytic plant remains and include decomposed woody and herbaceous material, overlaying Coastal Plain sandy marine sediments, with poor and very poor drainage and moderate to rapid permeability. Mollisols have sandy and loamy marine sediments as parent material with poor drainage and very slow to rapid permeability.

The soil orders appeared to occur in a concentric scheme (Fig. 7-1). The shallow soil was located at the north end of the transect. Due to leveling of soil during bed construction, eight sampling sites had a C horizon as the first layer. Their thickness varied from 10 to 25 cm, indicating the high variability in topography of the original site. With the exception of the Histosols and one of the Mollisols,

Table 7-2. Parent material and soil classification at the sampling points for grove A.

Tree number	Distance from the road, m	Parent material	Soil classification
5	12	Sandy and loamy marine sediments	Winder-1 s (Typic Glossaqualfs)
12	36	Sandy and loamy marine sediments	Boca-1 a (Arenic Ochraqualfs)
27	81	Loamy and clayey marine sediments	Chobee-1 fal (Typic Argiaquolls)
36	120	Decomposed organic material over loamy and clayey marine sediments	Nittaw muck (Terric Medisaprists), loamy†
41	150	Decomposed organic material over loamy and clayey marine sediments	Kaliga muck (Terric Medisaprists)
52	210	Loamy and clayey marine sediments	Chobee-2 al (Typic Argiaquolls)
54	216	Sandy and loamy marine sediments	Winder-2 la (Typic Glossaqualfs), fine-loamy
84	306	Marine sands over limestone	Hallandale-1 la (Typic Psammaquents)
85	309	Marine sands over shallow limestone	Hallandale-2 le (Typic Psammaquents)
96	342	Marine sands over shallow limestone	Boca-2 a (Arenic Ochraqualfs)
113	393	Marine sands over shallow limestone	Boca-3 a (Arenic Ochraqualfs)

† Muck layer is actually too thin to be a true Kaliga. The muck surface has thinned possibly due to oxidation and compaction. This pedon actually is Chobee with a thin muck surface (Nittaw series).

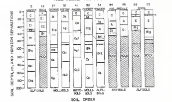

Figure 7-1. Classification of soils at 11 locations along a 400-m transect in grove A. The dotted line indicates the height of the water table on 8 August 1985.

all the other sampling points had a mixture of mineral and humified organic material (A) present before grove setting. Only the five Alfisols had a zone of eluviation (E), with the characteristic that only the two Alfisols at the south end of the bed had a subdivision of the E horizon. Presence of an illuviation horizon (B) was observed only in the Alfisols order. All the B horizons had an accumulation of silicate clay (t), which is assumed to be an illuviation process. In several of the horizons about two-thirds of the sampling points showed that stagnant water had induced a reduced state (g). The broken line (Fig. 7-1) indicates the height of the water table at the time of sampling. In about half of the deepest horizons (C), an accumulation of alkaline earth carbonate was found.

Figure 7-2 shows the horizon designation for groves B, C, D, and E. Three soil orders (Alfisols, Mollisols, and Spodosols), and five soil series (Floridana, Holopaw, Myakka, Oldsmar, and Smyrna) were identified. Although the soil was disturbed during bed construction operations, soils in grove C were identified as phases of Holopaw and Floridana soil series on the basis of color and thickness of the epipedon and the depth to the argillic horizon.

A plowed or disturbed soil surface (Ap) was a characteristic for most of the sampling points. Only one point had a 'fill' (C) horizon over the original soil surface. The depth and the thickness of the E horizon was variable in all orders. The E horizon in the Myakka and Floridana soils was subdivided into E1 and E2. There was a second eluvial horizon (E') after the spodic horizon in the Myakka and Smyrna soils. The Myakka and Smyrna soils were very similar. The illuvial horizon (B) was present in all soils, and showed a silicate clay

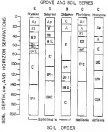

Figure 7-2. Classification of soils in groves E, D, B, and C.

accumulation in Oldsmar, Floridana, and Holopaw series. The accumulation of organic matter (h) was very evident in the Spodosols order. The unconsolidated geologic strata (C) were found only in the Oldsmar and Holopaw series. Furthermore, carbonates (k) were located in the last horizon of the Holopaw series.

Figure A-1 shows a generalized profile description of the soil orders present in Florida. Only one of the soils, Nittaw, in grove A seems not to fit the general description of soil orders present in Florida.

Horizon Boundaries

In grove A, a tendency existed for an abrupt (a) distinctness between horizons at the north half of the bed, compared to the south half. A gradual (g) distinctness was found mainly in the lower horizons of the Chobee-1 and -2, Nittaw, Kaliga, and Winder-2 series. No pattern of distribution of clear (c) distinctness existed between horizons. Most of the topography of the boundary was smooth (s), with most of the wavy (w) boundary being at the lower horizons of the Boca-1, Chobee-1 and -2, Nittaw, and Kaliga series.

Texture

In grove A about 0.2 of the horizons had a sandy texture (Fig. 7-3). Most of the horizons (0.78) were sandy loam, sandy clay loam, or loamy sand. In these textural classes, sand content is higher than 50%, silt is between 0 and 40%, while clay may be between 0 and 35%. Another feature to note is that most of the loamy sand horizons were the deepest at most of the sampling position. The C horizons were mostly sandy loam and sandy clay loam. No other pattern of textural distribution was observed.

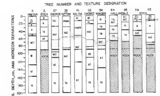

Figure 7-3. Textural classification of horizons at 11 locations along a 400-m transect in grove A.

Structure

Structure is not a strong characteristic of Florida soils; however, in Fig. A-2 some general descriptions about structure for grove A are given. Most of the horizons had structural units ranging from mainly medium size, to fine size, with very low distinctness, and blocky and granular form.

Consistence

The consistence of the soil in grove A was described in the moist condition. The presence of the water table led to a description in the wet condition. Deepest horizons were mainly slightly sticky-slightly plastic, with some slightly sticky-non plastic consistence. Most of the soil above the water table was friable and very friable, followed in frequency by loose and firm consistence. The soil with firm consistence was confined to the depth of 20 to 90 cm, which highly correlates with the Bt and Btg horizons which were above the water table.

Color

Most of the soil horizons in grove A had a 10YR color (moist), while some of the wet horizons had a 5Y or 5GY designation.

Water Content

Soil gravimetric water content at the time of sampling in grove A varied from 0.04 to 0.91 kg kg^{-1} (Fig. 7-4). Lower horizons in the muck area had high water content. The first horizon (Oa) for the Nittaw had the highest water content. Since this water content is on a weight basis, the Oa horizon in the Kaliga series should show a very low water content if expressed on a volume basis. Low water content was associated with the E horizons. Excluding the highest water content value, 0.75 of

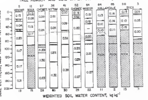

Figure 7-4. Water content of horizons at 11 locations along a 400-m transect in grove A.

the data were in the range of 0.11 to 0.25 kg kg^{-1}, with a general mean of 0.20 kg kg^{-1}.

Soil Penetrometer Resistance

Table 7-3 shows SPR values at the tree dripline as a function of soil depth along a transect across the eleven sampling points on 8 Aug. 1985. Empty cells indicate presence of rock. Generally, SPR values increased with depth; however, for the Kittaw end for the Chobee-2 series, very uniform and low SPR values were found throughout the soil profile. The SPR variability within each sampling point was lower at the middle of the bed and increased at both ends. Larger variations were observed in the three Boca and in Winder-1 series, which were located at both north and south ends of the bed. Figure 7-5 shows SPR mean values for each of the horizons. An SPR value of seven was used when rock was present in order to estimate the weighted mean in the top 90-cm depth. Lower values were found at and around the muck area, while higher values were found mainly in the E horizons. To a degree, there was a relationship between SPR values (weighted by horizon thickness in the top 55 cm of soil) and the different soils (Fig. 7-6). The Mollisols and Histosols were associated with lower SPR values, while the Entisols and Alfisols had the higher SPR values.

The SPR mean values were <0.5 MPa for Kittaw and Chobee-2 and >2.5 MPa for Hallandale-1 and Winder-1 series (Fig. 7-6). Also, SPR varied widely (1.5 versus 2.8 MPa) within a given soil series (e.g., Winder). Since root growth is strongly influenced by soil compaction, the wide range in SPR values gives an indication of the variability should exist in rooting patterns among soils. It is not surprising that trees grown

Table 7-3. Soil penetrometer resistance (SPR) at the tree dripline in 11 sites at the citrus grove A on 8 August 1985

Soil depth	5 Winder 1	12 Boca 1	27 Chobee 1	3[illegible] Nittaw	41 Kaliga	52 Chobee 2	5[illegible] Winder 2	[illegible] Hallandale 1	85 Hallandale 2	96 Boca 2	113 Boca 3
cm	SPR (MPa)										
5	0.52	0.00	0.26	0.36	1.26	0.28	0.25	0.54	0.56	0.49	0.00
10	1.37	0.39	1.83	0.54	1.67	0.64	1.10	1.18	1.10	0.98	0.85
15	2.39	1.08	1.18	0.54	1.64	0.56	1.67	2.45	1.21	1.24	1.14
20	2.45	2.36	1.08	0.25	1.18	0.46	1.90	3.35	1.37	1.31	1.11
25	2.26	3.04	1.44	0.20	1.11	0.49	1.57	2.75	1.11	2.22	1.96
30	3.14	3.58	1.29	0.18	1.23	0.59	1.21	2.65	1.34	3.45	2.11
35	3.83	3.89	1.05	0.56	0.98	0.59	1.28	2.67	1.47	4.17	2.45
40	4.42	4.02	1.31	0.54	1.16	0.57	1.31	3.08	1.42	4.42	2.85
45	4.55	3.73	1.11	0.67	1.00	0.59	1.28	2.85	1.47	3.19	3.09
50	4.12	2.26	1.14	0.77	1.01	0.59	1.43	3.08	1.78	1.13	3.73
55	1.57	1.37	1.06	0.77	1.05	0.57	1.47	3.30	2.45	0.35	3.93
60	0.79	1.11	1.03	0.67	1.03	0.56	1.50	2.98	2.98	0.95	3.91
65	0.79	1.37	0.75	0.49	0.77	0.49	1.21	2.81	2.75		1.91
70	1.57		0.67	0.54	0.70	0.51	1.11		2.52		1.52
75	2.03		0.62	0.52	0.75	0.51	0.98		2.49		2.16
80	2.49		0.62	0.44	0.79	0.44	0.90				3.43
85	2.55		0.61	0.36	0.79	0.31	0.81				
90	2.45		0.61	0.28	0.72	0.31	0.75				
Distance, m	12	36	81	120	150	210	216	306	309	342	393
Mean	2.41	2.17	0.98	0.48	1.05	0.50	1.21	2.59	1.73	2.14	2.26
SD	1.23	1.39	0.38	0.18	0.29	0.11	0.38	0.82	0.72	1.42	1.17
CV(%)	51	64	39	38	28	22	31	32	42	66	52

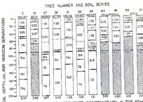

Figure 7-5. Soil penetrometer resistance means by horizon at 11 locations along a 400-m transect in grove A.

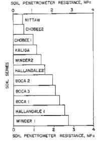

Figure 7-6. Mean soil penetrometer resistance (weighted by horizon thickness in the top 55 cm of soil) for each sampling point at grove A. Soil series are identified.

in muck soils (low SPR) have a longer life expectancy than trees grown in shallow and/or compacted soils.

Tables 7-4 and 7-5 show SPR at two sampling points on 5 June 1985. Since the soil at the dripper (Table 7-4) was at field capacity, SPR were lowest compared to the SPR at about 100 cm from the tree trunk (Table 7-4) and to the SPR at the tree dripline (Table 7-3). Tables 7-3 to 7-5 show that SPR values were dependent on the sampling point and were related to the soil water content. At tree numbers 85 and 96 (in Table 7-5), the soil below 10- to 15-cm depth was too hard to take SPR readings, though there was not presence of rock at that depth. Even when the soil at the dripper was at or above field capacity, some soil series, mainly at the ends of the transect, were high in SPR values. This increase in SPR with depth was observed for both the dry and wet conditions, as also was the uniformity of SPR with depth for the muck areas.

The high dependence of SPR on soil water content is shown in Fig. 7-7. A water content of around 0.25 kg kg^{-1} was the critical point for the SPR increase. Apparently the relationship between SPR and water content was influenced by the type of horizon and the presence of specific features within each horizon. For the B horizons soil penetrometer resistance was high and soil water content low. The A, E, and C horizons were somewhat scattered in Fig. 7-7. That dispersion may be due to the specific features used to subdivide each horizon. The lowest SPR values were associated with horizons possessing carbonates. The presence of Ca may lower the mechanical impedance due to soil flocculation. Note that horizon designation is made according to

Table 7-4. Soil penetrometer resistance (SPR) at the dripper in 11 sites at citrus grove A on 5 June 1986.

Soil depth	Tree number and soil series										
	5	12	27	36	41	52	56	84	85	96	113
	Winder 1	Boca 1	Chobee 1	Nittaw	Kaliga	Chobee 2	Winder 2	Hallandale 1	Hallandale 2	Boca 2	Boca 3
cm	SPR (MPa)										
5	1.0	0.5	0.2	0.4	0.3	0.2	0.4	0.4	0.4	0.3	0.5
10	1.5	0.8	0.4	0.5	0.2	0.2	1.1	0.5	0.6	0.7	0.7
15	2.0	1.6	0.6	0.5	0.1	0.3	1.6	0.6	0.7	1.3	0.9
20	2.5	2.9	0.6	0.3	0.3	0.6	2.0	0.6	0.6	2.0	1.1
25	3.5	3.8	0.5	0.3	0.4	0.9	0.9	0.9	1.3	2.9	2.4
30	4.5	4.4	0.6	0.4	0.4	0.9	0.6	1.1	1.8	3.7	3.4
35	5.2	4.6	0.6	0.6	0.6	0.8	0.7	1.4	1.9	4.1	3.6
40	4.0	5.5	0.5	0.7	0.6	0.6	0.6	1.6	2.0	2.4	4.3
45	2.7	3.4	0.4	0.8	0.5	0.5	0.9	1.6	2.1	1.2	4.2
50	2.5	1.8	0.4	0.9	0.6	0.5	1.2	1.6	2.4	0.9	2.4
55	2.6	1.2	0.4	0.7	0.6	0.5	1.4	1.6	2.3	0.7	0.6
60	2.6	1.4	0.4	0.6	0.6	0.6	1.3	1.6	1.9	1.0	1.1
65	2.6	2.3	0.3	0.5	0.5	0.6	1.2	1.5	1.1	6.6	2.7
70	2.5	2.4	0.3	0.3	0.5	0.4	1.1		4.5	2.1	4.1
75	2.7	2.8	0.4	0.2	0.4	0.3	1.1			3.6	5.0
80	2.5	7.5	0.4		0.4	0.4	0.8			3.8	
85	2.3		0.5		0.2	0.4	0.7			3.6	
90	2.7		0.5		0.1	0.3	0.7			3.6	

Table 7-5. Soil penetrometer resistance (SPR) at 11 sites located about 1 m from the dripper in grove A on 5 June 1986.

Soil depth	Tree number and soil series										
	5	12	27	36	41	52	56	84	85	95	113
	Winder 1	Boca 1	Chobee 1	Nittaw	Kaliga	Chobee 2	Winder 2	Hallandale 1	Hallandale 2	Boca 2	Boca 3
cm	SPR (MPa)										
5	2.5	2.2	0.9	1.3	0.0	0.9	2.0	1.4	4.5	4.2	1.9
10	3.5	2.5	0.9	1.3	0.8	0.8	3.4	2.6	6.5	4.1	1.6
15	3.5	2.6	0.7	1.5	1.1	0.8	4.1	2.3		3.5	1.6
20	3.4	2.7	0.5	0.3	1.4	1.1	4.6	2.2			1.6
25	4.0	3.5	0.5	0.8	2.2	1.1	2.4	2.4			2.9
30	5.5	5.5	0.6	1.2	2.3	1.5	1.4	3.8			3.4
35	6.0	5.9	0.6	1.4	2.2	2.4	1.6	4.5			3.6
40	4.5	5.5	1.0	0.8	2.0	2.4	1.0	4.6			3.4
45	3.5	5.1	1.2	1.1	1.2	2.6	1.1	4.4			3.9
50	3.3	4.1	1.5	1.7	0.9	2.8	1.3	6.5			3.9
55	4.5	4.0	1.5	1.6	0.8	2.4	1.6	6.5			1.5
60	3.4	3.9	1.5	1.5	0.6	2.8	1.4	6.2			1.2
65	3.4	3.7	1.3	1.1	0.4	1.9	1.4	4.2			1.4
70	3.5	3.7	0.7	0.9	0.3	1.3	1.3	2.7			1.9
75	4.0	4.3	0.6	0.8		0.8	1.2	2.0			2.1
80	4.5	3.1	0.4	0.4		0.6	1.2	1.2			2.5
85	4.0	1.7	0.4	0.3		0.4	0.7	3.7			
90	3.1	1.7	0.4	0.2		0.4	0.7	3.4			

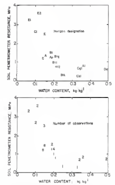

Figure 7-7 Soil penetrometer resistance (SPR) as a function of the soil water content (GWC). Top section of the figure shows values of SPR and GWC for specific genetic horizons. Values were weighted by thickness of horizons. Bottom section of figure shows the number of observations contributing to the estimate of each mean.

specific soil characteristics such as texture, structure, etc., which may influence more directly the relationship between SPR and water content.

The SPR values as a function of depth for groves B, C, D, and E are shown in Figs. 7-8 and 7-9. For all sites, SPR increased with depth; however, for the Floridana soil the rate of increase in SPR values was the lowest of all five sites. The highest values were associated with the Oldsmar series at soil depths below 60 cm. The variability (SD) increased as SPR increased.

For the Spodosols, however, Smyrna had the highest variability while Myakka had the least variability in the top 30 cm of soil. At the Holopaw site, SPR readings were not taken below 50-cm depth. The E horizon was observed to be very difficult to penetrate, even at high soil water content. From visual observations, it was concluded that unless the sand in the E horizon was coated, a high impedance to penetrability was observed. Soil penetrometer resistance values exceeded 3 MPa below the 45-cm depth for the Holopaw, Smyrna, and Oldsmar series, but did not exceed 3 MPa in the whole profile for the Myakka and Floridana series.

Soil pH

Soil pH values for grove A depended on depth and sampling point (Fig. A-3). Lowest pH values were found in the Glossaqualfs and Mollisols, which were located near the middle of the bed. Soil pH increased with distance from the swale area. For specific sampling points, deeper horizons had high pH values compared to the soil layers at or near the surface. However, as large differences were observed among horizons; therefore, pH values were more or less homogeneous through each profile.

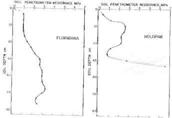

Figure 7-8. Soil penetrometer resistance as related to soil depth for the Floridana and Holopaw soil series.

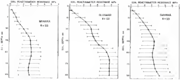

Figure 7-9. Soil penetrometer resistance as related to soil depth for the Myakka, Smyrna, and Oldsmar soil series. Horizontal lines represent the standard deviation.

The largest changes in pH values were observed between muck and mineral soils.

Water Uptake by Trees

In grove A, water uptake varied from 0 to 0.53 $cm^3\ s^{-1}$. As expected, water uptake was high for some trees in the muck area. That is the area that still sustains trees from the original grove. The volume of water uptake by trees was negatively associated with soil pH (weighted mean in the top 40 cm of soil) (Fig. A-4). Trees that were located in soil low in H^+ concentration (high pH) had less water uptake. This is a well-known fact among people working with citrus blight in Florida, but as of now, has not being satisfactorily proven. There was a better association of water uptake with soil pH than with SPR.

Summary and Conclusions

No concerted effort has been made to relate soil compaction to citrus tree condition. Soils in five citrus groves were chosen to represent variation in the 'flatwoods' area used for citrus production. Two groves (A and C) were chosen near Ft. Pierce. Another grove (B) was near Indiantown, while the other two groves (D and E) were near Arcadia.

The greatest soil variability was found in grove A. Four soil orders (Alfisols, Entisols, Histisols, and Mollisols) were identified, together with six soil series (Boca, Chobee, Hallandale, Kaliga, Nittaw, and Winder). Soils in groves B, D, and E were Spodosols, with respective soil series of Oldsmar, Smyrna, and Myakka. Mollisol and Alfisols orders were identified in grove C, with respective soil series of Floridana and Holopaw.

Soil penetrometer resistance (SPR) in grove A was dependent on soil type. The Kaliga, Nittaw, and Chobee series had the lowest SPR values. The SPR in these soils was very uniform across all the soil profile, while the SPR for the other soils increased with depth. It reached values as high as 4 MPa around the 45-cm depth, after which SPR decreased. The SPR for Spodosols was high, reaching mean values of 5 MPa for the Oldsmar soil. Soil penetrometer resistance was not higher than 3 MPa for the Floridana soil in all the profile, and for the 45-cm depth for the Malopaw depths.

In grove A, soil pH varied from 4.1 (Nittaw) to 6.5 (Bass). Soil pH was quite uniform with depth at each sampling position, while large differences were found among soils. Soil pH in the top 40-cm depth was negatively related to the amount of water uptake by trees when water was injected through the tree trunk. Trees affected with blight were observed only in grove A, and were present only outside the muck area.

The spatial variability in selected soil characteristics within a grove and among groves was presented. The large soil variability found is not surprising. During soil formation, climate, flora, and fauna each contributed to soil heterogeneity. Lately, man imposed new changes to satisfy his needs. Plants grow in a wide variety of soil conditions, though the optimum soil conditions should be those on which the species was developed. The imposition of new environmental conditions should stress plants in an unpredictable way. Thus, it should not be surprising that plant stresses cannot be fully understood. The study of environmental factors may lead to a better understanding of plant behavior as the plant responds to its environment. There are so many factors, however, that it would be difficult to study all of their

interactions at once. For the present study, it can be stated that soil physical and chemical characteristics may play an important role in citrus behavior related to plant stress. The numerous interactions among soil characteristics make it difficult to draw satisfactory conclusions. It was shown, however, that the soil might contribute greatly to stress of trees, which then may cause them to become more susceptible to the incidence of pathogens.

CHAPTER VIII
OVERALL SUMMARY AND CONCLUSIONS

Field studies were conducted to evaluate soil compaction in two soybean experimental areas and five citrus groves. This dissertation is divided into eight chapters. Chapter I introduced the need for the studies. Chapter II reviewed the literature for the total study. Chapter III evaluated the relationships among the factors of soil penetrometer resistance, bulk density, and water content at the end of an 8-yr soybean tillage system. Chapter IV related soil compaction to tillage treatments and soybean biomass production. Chapter V related soil compaction and water management treatments to soybean rooting patterns. Chapter VI related wheel-induced soil compaction to soybean rooting patterns. Chapter VII presented results of describing soil compaction in soils used for citrus production in the 'flatwoods'.

Results for different soil tillage systems showed that the relationship between soil penetrometer resistance and bulk density depended upon factors such as tillage, subsoiling, traffic, position, and soil depth. For example, the association between soil penetrometer resistance and bulk density was less evident for the non-disturbed soil than for the highly disturbed soil.

Subsoiling to 33 cm reduced soil penetrometer resistance to less than 0.4 MPa in the top 20 cm, but compressed the soil vertically below 35 cm, and extends at this depth laterally as far as 30 cm. Results from this study demonstrated that in-row subsoiling is a necessary practice to maintain soybean yields in a no-tillage soybean system.

The water management study was conducted in the IFAS Irrigation Research and Education Park. After seeding soybeans, a uniform water rate was applied for 41 d, at the end of which time four differential amounts of water were applied over a 35-d period. Water amounts (including rainfall) over the 35-d period were 160, 318, 384, and 411 mm for the following treatments: very low, low, medium, and high irrigation frequencies, respectively. For all treatments, soil penetrometer resistance increased with depth to a maximum of between 2.6 and 3.1 MPa at the 45-cm depth, after which it decreased. Below 40 cm, soil penetrometer resistance increased slightly with an increase in amount of water applied. Ninety percent of the soybean roots were in the upper 30-cm depth for the high-frequency treatment and in the upper 75-cm depth for the very low frequency treatment. Soil compaction increased by 34% in the top 35-cm depth and root density decreased 26% in the top 15-cm depth when measured 76 d after two passes of tractor wheels in the row were made prior to planting. A SPR value of 2.5 MPa was found to be critical for root growth.

Soil penetrometer resistance varied widely when comparing different soil series used for citrus production. Values ranged from 0 to 7 MPa, being lowest for Myakka, Kaligo, and Chobee series, and highest for the Oldsmar series. Results suggest that soil compaction may play a role in reducing the lifespan of citrus trees.

Recommendations for future research include: (1) Determination of how often in-row subsoiling is required for optimum sustained crop production. (2) Assessment of spatial variability in soil compaction and citrus blight incidence, which has been observed to occur both in random and non-random patterns. The choice of sampling scheme,

statistical analysis to be employed, and observational interval for soil measurements continues to perplex the soil scientist interested in relating soil properties to development and incidence of plant stress. (3) Use ground-penetrating radar technology to help correlate variations in soil properties with incidence and distribution of citrus blight. This includes bed formation in 'flatwood' areas for citrus production, beds that strongly influences both surface and subsoil compaction and resultant root development. Research is needed on the construction of beds for an optimum root environment and maximum tree longevity.

APPENDIX

Table A-1. Analysis of variance for soil volumetric water content (22-23 May 1985) and gravimetric water content (28 May and 3-4 June 1985).

Source of variation	Dates of sampling				
	df	22-23 May Level of significance	df	28 May Level of significance	3-4 June Level of significance
Model	23	0.01†	35	0.01	0.01
Main plots:					
Replicates	1	NS	3	NS	NS
Irrigation	3	NS	3	0.01	NS
Rep. x Irr. (a)	3	–	9	–	–
Sub plots:					
Depth	4	0.01	5	0.01	0.01
Irri. x Depth	12	NS	15	0.01	NS
Error (b)	16	–	60	–	–
Total	39	–	95	–	–
R^2		0.85		0.87	0.88
CV (a), (%)		33		16	35
CV (b), (%)		10		15	15
Mean		9.88		4.27	3.24

† NS = not significant at $P < 0.05$; – = not applicable.

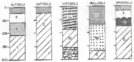

Figure A-1. Generalized profile description of the soil orders in Florida.

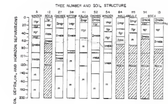

Figure A-2. Soil structure of horizons at 11 locations along a 400-m transect in grove A.

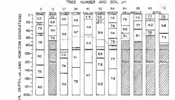

Figure A-3. Soil pH (1:1, soil:water) of horizons at 11 locations along a 400-m transect in grove A.

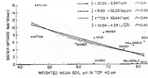

Figure A-4. Water uptake ($\hat{Y}$) by citrus trees as affected by the soil pH (0-40 cm) in grove A.

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BIOGRAPHICAL SKETCH

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He received his Bachelor of Science degree from the Facultad de Agronomia de la Universidad de Nuevo Leon in 1970. For 3 years he was employed as a researcher at the National Institute of Agricultural Research, where he worked with soil fertility and its relation to annual crops.

From 1973 to 1976 he studied for his Master of Science degree in the Soil Science Department at the Colegio de Postgraduados, Chapingo. He worked 7 years at the National Institute of Agricultural Research with soil fertility and its association to citrus production.

In August 1982, he was admitted to the Graduate School of the University of Florida and became a candidate for the degree of Doctor of Philosophy in the Soil Science Department.

The author is married to the former Beatriz E. Chimas B., and they have four children—Luciano, Benjamin, Beatriz, and Lina.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

David V. Calvert

David V. Calvert
Professor of Soil Science

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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This dissertation was submitted to the Graduate Faculty of the College of Agriculture and to the Graduate School and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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